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Comparison Studies of Hierarchical Cluster-Based Routing Protocols in Wireless Sensor Networks

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Abstract

The usage of the appropriate routing protocol algorithm in wireless sensor network (WSN) research is an important issue. Depending upon the deployed network topology, routing protocols can be classified in many ways including hierarchical cluster-based routing protocol. The hierarchical cluster-based routing protocol is pursuing an energy-efficient way to reduce the overall energy consumption within the monitoring cluster area by performing data aggregation along with data fusion. The objective of this study is to present a state-of-the-art survey on selected hierarchical cluster-based routing protocols in WSNs. In this paper, hierarchical cluster-based routing protocol algorithms are reviewed and compared with their advantages and disadvantages along with their main contributions. Additionally, each hierarchical cluster-based routing protocol algorithm is analyzed by comparing the measurement parameters of their performance.

1 Introduction

Over the past few years, wireless sensor networks (WSNs) have been focused by many researchers in the fields of computer networking or other networking applications such as cloud computing [2], environmental monitoring [3], security surveillance [16], real-time target tracking [17], health care [18] and more. In general, WSN consists of at least one sensor node or a sink node called a base station, and a number of sensor nodes deployed in the network. Those observed sensor nodes in the network sense and collect acquired data from their environments to develop some local processing, intercommunicate with each other to perform the required data aggregation, and then send (or receive) the aggregated data to (or from) the base station, which can serve as a destination node for the sensor network.

In the hierarchical cluster-based routing protocols to save total energy consumption of WSNs [19], the routing cluster is created and a head node is assigned to each cluster. The head nodes are centroids in their groups to collect and aggregate information from their respective clusters. The head nodes are also forwarding the aggregated data to the base station. Another main idea of developing a cluster-based routing protocol is how to improve the network reliability by reducing the network traffic towards the sink [21]. It has been demonstrated that cluster-based protocols exhibit better energy consumption and performance when those developed routing protocols are compared to other classified protocols including flat network topologies, location-based, and energy-aware cluster-based [20] and so on.

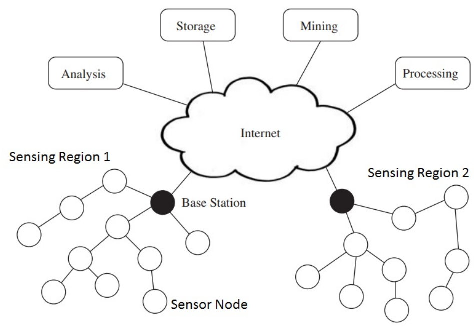

Figure 1: Fundamental Wireless Sensor Network Architecture [1]

Even though these sensor nodes in the network area can communicate with each other, these sensor nodes may have some constraints from the resources, which are connected with, such as the lack of memory, low battery power, noise signals for processing, path computation and communication capabilities [22]. Since these sensor nodes are associated with remote access areas along with their sensor networks' research interests, the sensor nodes within the wireless sensor network require to communicate with each other frequently based upon their applications. These activities can also improve data dissemination in large networks even though, during data dissemination in WSNs, data transmission consumes more energy than data processing in a sensor node.

In this paper, Section 2 shows the literature review of different kinds of hierarchical cluster-based routing protocols. Section 3 presents the compared evaluation measurements for those selected hierarchical cluster-based routing protocols. Section 4 draws the analyses by the comparison of those selected hierarchical cluster-based routing protocols. Finally, in Section 5, the conclusion of the comparison studies about the examined hierarchical cluster-based routing protocols is described.

2 Hierarchical Cluster-Based Routing Protocols in WSNs

Mainly, there are three types of routing protocols in WSNs depending on, network structure, routing criteria and topology [23]. Among three types of routing protocols, hierarchical cluster-based routing protocols are under the type of the network structure. Hierarchical cluster-based routing protocols are utilized to perform energy efficient routing related to scalability and efficient communication among the employed sensor nodes in wireless sensor networks. In a hierarchical architecture, higher energy nodes are employed to process and transmit the signal information while low energy nodes can be used to detect the proximity of the target. As a result, hierarchical cluster-based routing protocol strategies are relatively efficient to consume less energy among the sensor nodes within a cluster. Those techniques are also able to perform data aggregation and data fusion with a reduced number of transmitted messages to the base station. In general, using two layers of hierarchical routing, one layer is used for the selection of cluster heads within a cluster as a node selection stage and the other layer is used for the routing of related sensor nodes.

2.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

Low-Energy Adaptive Clustering Hierarchy (LEACH) developed by Heinzelman and et al. [4] is one of the early stage technologies in the clustering-based routing protocol. It was designed for wireless sensor networks (WSNs) to analyze a protocol architecture that combines the ideas of energy-efficient cluster-based routing and media access with application-specific data aggregation to achieve good performance for system lifetime, latency, and application-perceived quality, and to minimize the power consumption. In LEACH, the self-organization of sensor nodes into the number of clusters is used when one sensor node is acting as a cluster head (CH) at each round. LEACH also uses a randomized rotation of the cluster head position with the high-energy to avoid the battery exhaustion for a single sensor. Additionally, LEACH performs data aggregation and data fusion to compress and reduce the size of data being sent to the base station (BS), which can enhance energy dissipation for prolonging the lifetime of the system. For the selection of the cluster heads, all sensor nodes generate a potential value randomly so that LEACH can deploy a distributed cluster formation technique that enables to arrange large numbers of nodes for themselves through adapting clusters and rotating cluster head positions to evenly distribute the energy to form a load balance among all the neighbor sensor nodes to save communication resources.

2.2 Threshold-sensitive Energy Efficient Protocols (TEEN)

A hierarchical routing protocol called, Threshold-sensitive Energy Efficient sensor Network protocol (TEEN) as a reactive network protocol, has been introduced by Manjeshwar and Agarwal [6]. TEEN divides sensor nodes twice for grouping clusters to detect the environment continuously in the sensed attributes with the sensed value (SV). Then, the clusters are formed. After the first clustering, TEEN separates the cluster head into the second level cluster head and uses two threshold values called, hard-threshold and soft-threshold to detect the sudden changes of the environment. Besides, to transmit data in the current cluster period by the nodes, the following conditions [6], which are "the current value of the sensed attribute is greater than the hard threshold and the current value of the sensed attribute differs from SV by an amount equal to or greater than the soft threshold," need to be true.

Important features of TEEN include its suitability for time critical sensing applications. Also, since message transmission consumes more energy than data sensing, so the energy consumption in this scheme is less than the proactive networks. The soft threshold can be varied. At every cluster change time, fresh parameters are broadcast and so, the user can change them as required.

2.3 Adaptive Periodic Threshold-sensitive Energy Efficient Protocols (APTEEN)

The prior methods, LEACH [4] and TEEN [6] have some limitations of their communication and data transfer depending upon the conditions of threshold values in the applied reactive networks. Hence, APTEEN was introduced and its main features were described by Manjeshwar and Agrawal [10]. APTEEN is a hybrid hierarchical clustering protocol that changes the periodicity or threshold values to compensate for the limited energy and memory constraints for the tiny sensor nodes. APTEEN also uses an adaptive clustering used in the TEEN protocol according to the user needs and the type of the application. In APTEEN, attributes (A) is a parameter which is a set of physical parameters that the user is interested in obtaining information about. The threshold is a parameter that consists of the Hard Threshold (HT) and the Soft Threshold (ST). The schedule is a parameter which is a TDMA schedule, assigning a slot to each node. Count time (CT) is a parameter which is the maximum period of the time between two successive reports sent by a node.

2.4 Power-Efficient Gathering in Sensor Information Systems (PEGASIS)

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [7] is one of the enhancement protocols over LEACH protocol, which can be considered as an optimal chain-based protocol when all sensor nodes have the same level of energy with minimizing its energy consumption and fade away at the same time. The sensor nodes in PEGASIS form a chain construction with a greedy approach to communicate with only their closest neighbor sensor nodes in the exploring area to extend network lifetime without forming multiple clusters [24]. Then, the sensor nodes wait for transmitting to the base station to reduce the amount of the required energy for each round of occurrences. Simultaneously, the network lifetime will be relatively increased by increasing the lifetime of each node in the targeted networks. Unlikely other hierarchical routing protocol, PEGASIS can also reduce the consumption of the required bandwidth through the communication process with their close neighboring sensor nodes and avoid cluster formation and uses only one node in a chain to transmit to the base station instead of using multiple nodes [25]. In PEGASIS, there are possibilities of excessive delays for some distant nodes on the internal chain structure to be in the situation of a bottleneck for the single leader sensor node [28]. Additionally, even though, in most cases, sensor nodes can be fixed or immobile in PEGASIS, some sensor nodes may be movable and affectable to the protocol functionality [26].

2.5 Stable Election Protocol (SEP)

Stable Election Protocol (SEP) [8] is an enhanced version of LEACH protocol as a heterogeneous-aware protocol to prolong the lifetime of nodes before the death of the first node. While every sensor node is initialized to the same energy level in LEACH, SEP with a different initial energy level is originally designed for two-level heterogeneous networks using weighted election probabilities of each node to select a cluster head by measuring the remaining energy in each node. The protocol includes two types of nodes such as advanced and normal nodes depending upon the amount of their initial energy in the network. Additionally, since advanced nodes have $(1 + \alpha)$ times more than the initial energy for the normal nodes, advanced nodes get more frequently elected as cluster heads. Hence, a uniform usage of node energy and prolong the lifetime of the network can be guaranteed. Therefore, advance nodes are made by cluster heads more often than normal nodes because advance nodes have more energy as compared to normal nodes [29]. The following relationships show how to calculate the desired percentage of cluster heads, p, for normal and advance nodes respectively.

For the normal nodes, the desired percentage of cluster heads is

$$p_{normal} = \frac{p_{opt}}{1+\alpha\times m} \tag{1}$$

and for the advanced nodes, the desired percentage of cluster heads is

$$p_{adv} = \frac{p_{opt}}{1+\alpha\times m} \times (1+\alpha) \tag{2}$$

where m is the percentage of advanced nodes, respectively, α stands for additional energy of advanced nodes, and p_{opt} is the optimal probability of a given node to become the cluster head. Along with the desired percentage of cluster heads, the threshold for normal nodes is

$$T(n_{normal}) = \begin{cases} \frac{p_{normal}}{1-p_{normal}(r\times mod(\frac{1}{p_{normal}}))} & if\ n_{normal} \in M' \\ 0 & otherwise \end{cases} \tag{3}$$

and the threshold for advanced nodes is

$$T(n_{adv}) = \begin{cases} \frac{p_{adv}}{1-p_{advl}(r\times mod\,(\frac{1}{p_{adv}}))} & if\ n_{adv} \in M'' \\ 0 & otherwise \end{cases} \tag{4}$$

Therefore, in SEP, the initial energy is increased by $\alpha \times m$ and hence overall performance/network lifetime increases so instability period decreases.

2.6 Hybrid Energy Efficient Distributed (HEED) Clustering Protocol

Hybrid Energy Efficient Distributed (HEED) [14] clustering algorithm is designed to select different cluster heads in a field according to the amount of energy that is distributed to a neighboring node. HEED is pursuing four goals as a routing protocol [27]; (1) prolonging network life-time by distributing energy consumption, (2) terminating the clustering process within a constant number of iterations/steps, (3) minimizing control overhead, and (4) producing well-distributed cluster heads and compact clusters. To select the cluster head nodes, the sensor node's residual energy and the intra cluster communication cost are used for the procedure [15]. There are three phases of its operations in HEED such as initialization phase, repetition phase, and finalization phase. As mentioned, since HEED clustering protocol is an energy-efficient clustering protocol, it uses the residual energy as a primary parameter and node degree and distance to neighbors as secondary parameters. HEED clustering protocol also extends the basic scheme of LEACH protocol with improving few advantages of LEACH protocol by selecting periodically cluster heads based on the combination of the residual energy from each node and each node's neighbor degree to achieve power balancing and increase the network scalability and lifetime.

2.7 Two-Tier Data Dissemination (TTDD) Protocol

Two-Tier Data Dissemination (TTDD) protocol [15] provides transmitting data to multiple mobile base-stations to resolve the sink node problem, which applies multiple sub-sink nodes and a sink node moving in the network [30]. When multiple sub-sink nodes are ready to transmit the data to the sink node considered as a data forwarding state [30], a node is selected as a source node to send data. With constructing a grid network using the selected source nodes only located at the intersection, a source node detects the location of the nearest adjacent intersection. Then, after the source node finds the nearest new intersection with applying the greedy algorithm, the data forwarding process continues until it finds the network edge or no further intersections. Thus, the sink node continues to transmit the data, called the data request to transmit a query packet, to the next closest source node. During this process, each intermediate intersection node stores the source information and further forwards the message to its adjacent intersections except the source node from which the message comes from. In this protocol, using a single path, the network lifetime is extended with acquiring its location.

3 Measurement Parameters of Performance in Hierarchical Cluster-Based Routing Protocols in WSNs

The following applied measurement parameters of the performance in hierarchical cluster-based routing protocols in wireless sensor networks are analyzed to compare the algorithms.

(1) Load Balancing

Load balancing is a measurement metric to prolong the network lifetime since Load balancing is a crucial issue where cluster heads are selected from available nodes in the network [31]. To form an efficient energy network, the uniform load distribution of the cluster heads is required to establish an evenly loaded network with saving the energy consumption.

(2) Path Establishment

The path establishment mechanism is used for detecting routes from a source node to the projected node to distinguish the different types of the hierarchical-based routing protocols.

(3) Algorithm Complexity

To terminate the program as fast as possible, time complexity or convergence rate needs to be simple as possible and depends upon the number of cluster heads or hops in the network or the number of sensor nodes in the network.

(4) Delivery Delay

The delivery delay is for measuring a time for the data transmission to estimate the closeness between sensor nodes and its base station for measuring affected based upon the usage of the limited node energy by the fault tolerance of the alternative path. It is important for real time applications in wireless sensor networks.

(5) Power Consumption

The restricted storage capacity of sensor nodes in the wireless sensor networks is a crucial point to prolong the network lifetime. Finding a new scheme to improve power consumption is also very important to power aware protocol, cross-layer optimization, and harvesting technologies to alleviate the power consumption constraints [32].

(6) Sensor Capability

There are two types of sensor networks for sensor capability such as homogeneous network and heterogeneous network. A homogenous network with randomly assigned cluster heads consists of sensor nodes with the same energy, computation, and communication resources. A heterogeneous network consists of sensor nodes with unequal capabilities in the heterogeneous network environment.

(7) Data Aggregation

Through the multiple sensor nodes in the sensor networks, data aggregation is a collection of the desired information in the sensed environment and then sends the acquired information to the base station to improve the network lifetime with the better energy conservation by decreasing the energy consumption of sensor nodes.

(8) Inter Cluster Structure

Inter cluster routing is the communication between the sensor nodes or cluster heads, and sink node. The inter cluster communication can send their data directly to the sink using a single-hop or perform the data transmission to sink using intermediate nodes using a multi-hop routing.

(9) Network Lifetime

Network lifetime can be measured by the number of rounds when the first node dies in the network. Network lifetime depends on the average energy consumption of a node per round. Hence, for the longer network lifetime, the low average energy consumption per round is required.

(10) Energy Efficiency

Applying inter and intra cluster communication to the clustering can affect the number of nodes to communicate with the other nodes in the long distance to consume less amount of energy.

(11) Cluster Stability

If the cluster density varies throughout the routing process, the stability of the routing process is various. Otherwise, the stability of the routing process is fixed.

(12) Network Scalability

A network is getting more scalable if the number of sensor nodes in WSNs is getting increased up to tens of thousands of nodes when the cost of sensor nodes in wireless sensor networks is getting reduced [32].

4 Analysis of Hierarchical Cluster-Based Routing Protocols

In Table 1, the examined algorithms are compared by advantages and disadvantages with main contributions.

Routing Protocols	Pros	Cons	Main contribution
LEACH	Energy saving Reduced control messages overhead Low complexity algorithm	Non-uniform distribution of cluster heads Selecting a cluster head without considering the remaining energy Transmitting data in one-hop	(1) Dynamical Sensor nodes from the cluster (2) Random selection of cluster heads (3) All cluster heads transfer the collected information to the sink node
TEEN	Control over the useful data transfer Suitable for time critical applications	Unsuitable for periodic report requiring applications Ability to waste time slots If the cluster heads in the communication range of each other, they may have lost because publishing is done only by cluster heads	The critical data reach the user almost instantaneously. The soft threshold can be varied, depending on the criticality of the sensed attribute and target application. It will also enhance the efficiency of wireless sensor networks
APTEEN	Supports three different query types: historical query, one-time query, and endless queries Lower energy dissipation	(1) Relatively long delay (2) The additional complexity required to implement the threshold functions and the count time	After cluster heads are decided, in each round, cluster head broadcasts attributes, threshold, schedule, and count time. It combines both reactive and proactive policies and provides periodic data collection and event detection.
PEGASIS	(1) Avoids so much clustering (2) Removes the clustering overhead	(1) Introduces the chain shaping overhead (2) Requires dynamical topology adjustment (3) It needs multi-hop data transmission from the sensor into the sink which leads to a packet delay problem.	(1) It is an enhancement over LEACH and it is a near optimal chain-based protocol. (2) It will focus to extend the network lifetime by communicating with its closest neighbor. (3) It will avoid a cluster formation and use only one node to communicate with the base station instead of with multiple nodes.
SEP	(1) Provide network stable region. (2) No need to collect information about the node's energy in each round. (3) Work with a small and large-scale network. (4) It doesn't require the prior distribution of the sensor nodes.	(1) It doesn't use the residual energy of higher-level nodes efficiently. (2) No guarantee of efficient deployment of nodes. (3) It cannot be applied to multi-level networks.	It is a routing protocol to produce the longer stability region with better energy consumptions for the more powerful nodes. It controls the heterogeneity of the node energy in the network to balance the sensitivity of heterogeneity parameters in the network.
HEED	(1) Balanced clusters. (2) Low message overhead. (3) Uniform and nonuniform node distribution. (4) Inter-cluster communication explained. (5) Outperforms generic clustering protocols on various factors.	(1) Nonuniform distribution of energy conception (2) High overhead (3) Repeated iterations complexes algorithm. (4) Decrease of residual energy forces to iterate the algorithm. (5) Nodes with high residual energy one region of a network.	(1) A distributed clustering is used. (2) The cluster head formation is based on node proximity to its neighbor and its residual energy. (The clustering process is divided into a number of rounds and in each round, Cluster head is selected based on residual energy of nodes that are not covered by any cluster head which results in increasing its probability of becoming a cluster head almost twice.)
TTDD	(1) It deals with the problems caused by multiple mobile sinks and sinks moving in large-scale WSNs. (2) Despite that it is effective in	(1) The routing of a forwarding path in TTDD is not the shortest path, thus it may lead to large latency for the long path. (2) The grid	(1) A heuristic solution to select cluster head (2) A grid-based routing protocol to provide query and data dissemination for multiple mobile sinks (3) The source node proactively

	high mobility scenarios, the overhead to build and maintain the overlay is significant, especially in periodic reporting scenarios, which are more traffic intensive than event-based reporting.	structure formation and query flooding cost large energy consumption. (3) TTDD requires that sensor nodes are stationary and location-aware and assumes the availability of an accurate positioning system that may not yet available in a real WSN.	creates a virtual grid structure throughout the sensor field with dissemination nodes located at the grid cross points. (4) It solves the sink mobility problem using a grid structure

Table 1: The Advantages and Disadvantages of Hierarchical Clustering Based Routing Protocols with Main Contributions

Table 2 shows the comparison of the examined routing protocols' performance.

Measurement Parameters	**LEACH**	**TEEN**	**APTEEN**	**PEGASIS**	**SEP**	**HEED**	**TTDD**
Load Balancing	Medium	Good	Medium	Medium	Good	Medium	Good
Path Establishment	Proactive	Reactive	Hybrid	Reactive	Reactive	Hybrid	Proactive
Algorithm Complexity	Low	High	Very High	High	Very Low	Medium	Low
Delivery Delay	Very Small	Small	Small	Very Large	Very Small	Medium	Very Large
Power Consumption	High	High	Medium	Maximum	Medium	Low	High
Sensor Capability	Homo-geneous	Homo-geneous	Homo-geneous	Homo-geneous	**Hetero-**geneous	Homo-geneous	**Hetero-**geneous
Data Aggregation	Yes	Yes	Yes	No	Yes	Yes	No
Inter Cluster Structure	Single-hop	Multi-hop	Multi-hop	Single-hop	Single-hop	Multi or Single-hop	Multi-hop
Network Life Time	Good	Very Good	Good	Very Good	Good	n/a	Good
Energy Efficiency	Very Low	Low	Medium	Low	Medium	Medium	Very Low
Cluster Stability	Medium	High	Very Low	Low	Medium	High	Very High
Network Scalability	Low	Low	Low	Very Low	High	Medium	Medium

Table 2: Comparisons of Hierarchical Clustering Based Routing Protocols

5 Conclusion

The most important issue in wireless sensor networks is how efficiently to use required resources in the current wireless sensor network. Some resources may not be available due to their environmental conditions or other deficient conditions such as power supply replacement for the energy supply or the reusability of sensor nodes in the network. If the above challenges can be resolved, the routing protocols in wireless sensor networks are getting more robust to perform their functionalities such as saving energy consumption in each node or the cost of network maintenance along with the longer lifetime of the deployed sensor network. Since the idea of the cluster-based routing scheme is mainly on developing an efficient method with less energy usage through data aggregation and the optimization of the number of messages sent to the central station. Particularly, hierarchical cluster-based routing protocol algorithms have been reviewed by presenting their comparison studies to provide some perspectives.

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