

A Survey on Hierarchical-Based Routing Protocols for Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) is a popular source of data-collecting and sensing mechanism for a wide range of applications, such as environment monitoring, agriculture, health, military and smart transportation. Every sensor node collects information from the environment and forwards this sensed data to Base Station (BS) through wireless link in either single-hop or multi-hop manner. This data collection and forwarding property of the sensor nodes dominate the main energy consumption factor of a network. These sensor nodes being equipped with low power batteries which may be difficult to replace, making it a major research area to design energy-efficient protocols. To overcome this problem the WSN puts new challenges particularly in designing of routing protocols. The protocols are divided into hierarchical-based, flat-based, and location-based routing protocols depends on the routing structure. However, the hierarchical-based routing protocols outperform the other routing types in saving energy, scalability, and extending lifetime of WSNs. Choosing a proper hierarchical routing protocol is an important and difficult task. Therefore, this paper concentrate on reviewing some of the recently hierarchical-based routing protocols that are created in WSNs. Moreover, a comparison between the reviewed protocols is examined in this survey depending on delay, network size, energy-efficiency, and scalability. Finally, we summarize and conclude the paper with future directions.

Keywords: Routing protocols, Energy efficiency, Wireless sensor networks, Cluster-based routing

1. Introduction

The importance of Wireless Sensor Networks is monitoring and collecting data from the environment. A WSN typically consists of sensor nodes and/or sink(s) that can move within the network. These sensor nodes are scattered in the sensor field and it can collect the local environmental information, process them into useful data packets, and send the packets to the sink node by multi-hop. The sink node transmits the packets to administrator via internet or GPRS. Most of these sensor nodes having limited battery life, limited transmission power, low memory and limited processing capabilities [1]. With the dramatic development of hard-ware technology, the CPU and flash memory are becoming very smaller, more powerful and cheaper. As a result, the memory and processing capabilities of sensor nodes will not be the most important problem for the application of WSNs. However, the battery technology has failed to obtain a breakthrough yet. Obviously, the energy volume of sensor nodes will be the key bottlenecks for the development of WSNs in a very long time. So the research going on improve the energy efficiency of WSNs, so as to prolong the network lifetime, is still the focus at present and in the future. The technical ways and methods of improving energy efficiency of WSNs mainly involve the energy efficient routing algorithms and clustering algorithms. Therefore, WSNs require effective mechanisms to utilize and resolve the limited resources [2].

Routing is one of these best mechanisms that prolongs the lifetime of network by reducing the energy consumption during this communication. The developed routing protocols can be grouped based on the routing structure into hierarchical-based, flat-based, and location-based routing protocols. According to collected works [3–11], the hierarchical-based routing protocols outperform the other routing types in saving energy, prolonging a lifetime of WSNs, and scalability. The hierarchical-based routing partitions the network into multiple groups. Each group contains one head node and others are member nodes. Member nodes only senses and delivers its sensed data to its related head node, while a head node is responsible for collecting and aggregating data of its member node and then transfers the aggregated data to sink. Hierarchical-based routing is a best solution for reducing energy consumption in WSNs due to reduction of redundant data transmission. The classification of the reviewed protocols is presented in this survey based on many different metrics. Moreover, we compare between the surveyed protocols on the basis of delay, network size, energy-efficiency, and scalability.

2. Routing Protocols in WSN

Routing in wireless sensor networks differs from conventional routing in fixed networks in various ways. There is no infrastructure, wireless links are unreliable, sensor nodes may fail, and routing protocols have to meet strict energy saving requirements. Many routing algorithms were developed for wireless networks in general.

Location-based Protocols : MECN, SMECN, GAF, GEAR, Span, TBF, BVGF, GeRaF
Data-centric Protocols : SPIN, Directed Diffusion, Rumor Routing, COUGAR, ACQUIRE, EAD, Information-Directed Routing, Gradient Based Routing, Energy-

aware Routing, Information-Directed Routing, Quorum-Based Information Dissemination, Home Agent Based Information Dissemination

Hierarchical Protocols : LEACH, PEGASIS, HEED, TEEN, APTEEN

Mobility-based Protocols : Sensor-Disjoint Multipath, Braided Multipath, N-to-1 Multipath Discovery

Heterogeneity-based Protocols : IDSQ, CADR, CHR

QoS-based protocols : SAR, SPEED, Energy-aware routing

2.1 Routing Approach

The challenge of data routing can have two broad methods, namely, classical-based method and optimized-based method.

Classical-Based Routing: In the classical-based routing, head nodes are selected randomly using the timer function, which causes an uneven traffic flow in different head nodes. Although they are suitable for applications of WSNs, they still have many challenges such as scalability, load balancing, connectivity, coverage, and robustness.

Optimized-Based Routing: Routing in WSNs puts new challenges for researchers as various classical protocols lack fault tolerance, energy-efficiency, connectivity, robustness and scalability. In this optimized-based routing, the head nodes are determined based on multi criteria to achieve the requirements of QoS.

2.2 Clustering Attributes The attributes of the clustering process have an important effect on the performance of hierarchical-based routing. The cluster properties and the sensor capabilities are the two main issues in the clustering attributes [12, 13].

2.3 Cluster Properties

In the hierarchical-based routing protocols, the characteristics of the formed clusters are used to differentiate between these clusters in terms of saving energy, load balancing, and lifetime.

Cluster Size: From the point of cluster size, the hierarchical-based routing protocols in MWSNs can be grouped into equal and unequal clustering. In the equal clustering protocols, all clusters have the same size, while in the unequal clustering protocols, clusters have different sizes. In general, unequal clustering protocols are used to balance the load among the nodes and solve the energy hole problem.

Cluster Density: Cluster density is the number of cluster members. Density of cluster affects the energy consumption of CH. Clustering protocols can be static clustering protocols and dynamic clustering protocols. In the former one, clusters have fixed density, but the cluster density in the second one is variable.

Intra Cluster Routing: Intra cluster routing is the communication between MNs and CH. This communication can be a single-hop or a multihop routing. In the single-hop

routing, MNs directly deliver their data to CH. However in the multi-hop routing, member nodes transmit their data to CH via relay nodes.

Inter Cluster Routing: Inter cluster routing is the communication between the sensor nodes/CHs and sink node. The inter cluster communication can be a single-hop or a multihop routing. In the single-hop routing, sensor nodes/CHs send their data directly to sink. In contrast to it, sensor nodes/CHs transmit their data to sink using intermediate nodes in the multihop routing.

Stability: The stability of routing process depends on the cluster density. If the cluster density is fixed, the stability of routing is said to be fixed.

2.4 Sensor Capabilities

Based on the resources of the sensor nodes, WSNs can be classified into homogeneous and heterogeneous networks.

Homogeneous Network: A wireless sensor network is said to be homogeneous if all of its sensors have the same storage, processing, battery power, sensing, and communication capabilities. In this type of networks, CHs are assigned according to a random manner or other criteria.

Heterogeneous Network: It consists of sensor nodes with different ability, such as different computing power and sensing range. Compared with homogeneous WSN, deployment and topology control are more complex in heterogeneous WSN. Therefore, the role of CHs is specified to sensor nodes that have more capabilities.

2.5 Protocol Operation

Depending on the protocol operation, the hierarchical-based routing protocols are divided into negotiation-based, query-based, multipath-based, coherent-based, and QoS-based routing.

Multipath-based: We can use multiple paths instead of single path so as to strengthen the network performance. For instance, the fault tolerance will be increased by maintaining multiple paths between the source and destination at the expense of improved energy consumption and traffic generation [14].

Query-based: In Query-based protocols, destination nodes transmit a query for data from a node through the network; a node sends the data that matches the query back to the node that commenced it.

Negotiation-based: These protocols use high-level data or information descriptors to remove redundant data transmissions through negotiation. Examples of negotiation-based routing protocols are the SPIN protocols.

QoS-based: In QoS-based routing, the network should balance between energy consumption and data quality. The network should satisfy certain QoS while transporting data or information to the base station. Sequential Assignment Routing (SAR) and SPEED are the examples of this type of protocols.

Coherent-based: In coherent routing, data is forwarded to aggregators after processing like time stamping and duplicate suppression. Coherent processing is normally selected in order to perform energy-efficient routing.

Non-coherent-Based: In non-coherent data routing, nodes can locally process the raw data before sent to another nodes for further processing.

3. Evaluation Parameters of Hierarchical Routing Protocols

In this survey, the various hierarchical routing protocols will be evaluated based on delay, network size, energy-efficiency, and scalability.

Delay: Delay is a time taken for transmitting a packet from the source to the sink. This delay provides a close estimation for the actual latency. Delay is an important factor for real time applications.

Network Size: Each hierarchical routing protocol is suitable for a certain kind of network, such as large-scale networks or small-scale networks. Surely, there are hierarchical routing protocols that perform well in both large-scale and small-scale networks.

Energy-Efficiency: Due to the limited energy of sensor nodes in WSNs, most of the hierarchical routing protocols are developed to save the energy of sensors and extend the network lifetime. Thus, the energy-efficiency is the main objective of the routing protocols.

Scalability: As the sensors are becoming ever cheaper, unlike the traditional networks, WSNs are becoming larger up to tens of thousands of nodes. Therefore, a routing protocol should be scalable for adding new sensor nodes.

4. Hierarchical-Based Routing Protocols of WSNs

The main aim of hierarchical-based routing in WSNs is saving the residual energy of each sensor node, prolonging the network lifetime, and ensuring the connectivity among the sensor nodes. Some of these sensor nodes, that are called CHs or leaders, are responsible for collecting and processing data and then forwarding it to sink, while the task of other nodes, which are called MNs, is sensing the sensor field and transmitting the sensing data to the head nodes. Hierarchical-based routing is a two-layer architecture, where head nodes selection is performed in the first layer and the second layer is responsible for routing.

4.1 LEACH:

Low Energy Adaptive Clustering Hierarchy (LEACH) is the first hierarchical cluster-based routing protocol for wireless sensor network which partitions the nodes into clusters, in each cluster a dedicated node with extra privileges called Cluster Head (CH) is responsible for creating and manipulating a TDMA (Time Division Multiple Access) schedule and sending aggregated data from nodes to the BS where these data is needed using CDMA (Code Division Multiple Access). Remaining nodes are cluster members. This protocol is divided into rounds; each round consists of two phases.

Setup Phase: In the setup phase, a sensor node selects random number between 0 and 1. If this number is less than the threshold $T(n)$, the node becomes a CH. $T(n)$ is computed as:

$$T(n) = \frac{p}{1 - p^{*(r \bmod 1/p)}} \quad \text{if } n \in G$$

$$0 \quad \text{otherwise}$$

r is the current round; p , the desired percentage for becoming CH; and G is the collection of nodes not elected as a CH in the last $1/p$ rounds. Each node decides independent of other nodes if it will become a CH or not. This decision takes into account when the node served as a CH for the last time. In the following advertisement phase, the CHs inform their neighborhood with an advertisement packet that they become CHs. [15] Non-CH nodes pick the advertisement packet with the strongest received signal strength. In the next cluster setup phase, the member nodes inform the CH that they become a member to that cluster with "join packet" contains their IDs using CSMA. After the cluster-setup sub phase, the CH knows the number of member nodes and their IDs. Based on all messages received within the cluster, the CH creates a TDMA schedule, pick a CSMA code randomly, and broadcast the TDMA table to cluster members. After that steady-state phase begins.

Steady-State Phase: Data transmission begins; Nodes send their data during their allocated TDMA slot to the CH. This transmission uses a minimal amount of energy (chosen based on the received strength of the CH advertisement). The radio of each non-CH node can be turned off until the nodes allocated TDMA slot, thus minimizing energy dissipation in these nodes. When all the data has been received, the CH aggregate these data and send it to the BS. [16]

4.2 PEGASIS

Power-Efficient Gathering in Sensor Information Systems (PEGASIS): In [17], an enhancement over LEACH protocol was proposed. The protocol, called Power-Efficient Gathering in Sensor Information Systems (PEGASIS), is a near optimal chain-based protocol. The basic idea of the protocol is that in order to extend network lifetime, nodes need only communicate with their closest neighbors and

they take turns in communicating with the base-station. When the round of all nodes communicating with the base-station ends, a new round will start and so on. This reduces the power required to transmit data per round as the power draining is spread uniformly over all nodes. Hence, PEGASIS has two main objectives. First, increase the lifetime of each node by using collaborative techniques and as a result the network lifetime will be increased. Second, allow only local coordination between nodes that are close together so that the bandwidth consumed in communication is reduced. Unlike LEACH, PEGASIS avoids cluster formation and uses only one node in a chain to transmit to the BS instead of using multiple nodes. To locate the closest neighbor node in PEGASIS, each node uses the signal strength to measure the distance to all neighboring nodes and then adjust the signal strength so that only one node can be heard. The chain in PEGASIS will consist of those nodes that are closest to each other and form a path to the base-station. The aggregated form of the data will be sent to the base-station by any node in the chain and the nodes in the chain will take turns in sending to the base-station. The chain construction is performed in a greedy fashion. Simulation results showed that PEGASIS is able to increase the lifetime of the network twice as much the lifetime of the network under the LEACH protocol. Although the clustering overhead is avoided, PEGASIS still requires dynamic topology adjustment since a sensor node needs to know about energy status of its neighbors in order to know where to route its data. Such topology adjustment can introduce significant overhead especially for highly utilized networks. Moreover, PEGASIS assumes that each sensor node can be able to communicate with the BS directly. It assumes that all sensor nodes have the same level of energy and they are likely to die at the same time. Note also that PEGASIS introduces excessive delay for distant node on the chain. In addition, the single leader can become a bottleneck. Finally, although in most scenarios, sensors will be fixed or immobile as assumed in PEGASIS, some sensors may be allowed to move and hence affect the protocol functionality.

An extension to PEGASIS, called Hierarchical-PEGASIS was introduced in [18] with the objective of decreasing the delay incurred for packets during transmission to the BS. For this purpose, simultaneous transmissions of data are studied in order to avoid collisions through approaches that incorporates signal coding and spatial transmissions. In the later, only spatially separated nodes are allowed to transmit at the same time. The chain-based protocol with CDMA capable nodes, constructs a chain of nodes, that forms a tree like hierarchy, and each selected node in a particular level transmits data to the node in the upper level of the hierarchy. This method ensures data transmitting in parallel and reduces the delay significantly. Such hierarchical extension has been shown to perform better than the regular PEGASIS scheme by a factor of about 60.

4.3 HEED

HEED is Hybrid, Energy-Efficient Distributed Clustering protocol. HEED extends the basic scheme of LEACH by using residual energy and node degree or density as a metric for cluster selection to achieve power balancing. It operates in

multi-hop networks, using an adaptive transmission power in the inter-clustering communication. HEED was proposed with four primary goals namely:

- (i) Prolonging network lifetime by distributing energy consumption
- (ii) Terminating the clustering process within a constant number of iterations
- (iii) Minimizing control overhead
- (iv) Producing well-distributed CHs and compact clusters.

In HEED, the proposed algorithm periodically selects CHs according to a combination of two clustering parameters. The primary parameter is their residual energy of each sensor node (used in calculating probability of becoming a CH) and the secondary parameter is the intra-cluster communication cost as a function of cluster density or node degree (i.e. number of neighbors). The primary parameter is used to probabilistically select an initial set of CHs while the secondary parameter is used for breaking ties. The HEED clustering improves network lifetime over LEACH clustering because LEACH randomly selects CHs (and hence cluster size), which may result in faster death of some nodes. The final CHs selected in HEED are well distributed across the network and the communication cost is minimized. However, the cluster selection deals with only a subset of parameters, which can possibly impose constraints on the system. These methods are suitable for prolonging the network lifetime rather than for the entire needs of WSN. [19],[20]

4.4 TEEN

TEEN (Threshold sensitive Energy Efficient sensor Network protocol) is a hierarchical clustering protocol, which groups sensors into clusters with each led by a CH. The sensors within a cluster report their sensed data to their CH. The CH sends aggregated data to higher level CH until the data reaches the sink. In this scheme, at every cluster change time, in addition to the attributes, the cluster-head broadcasts to its members the following:

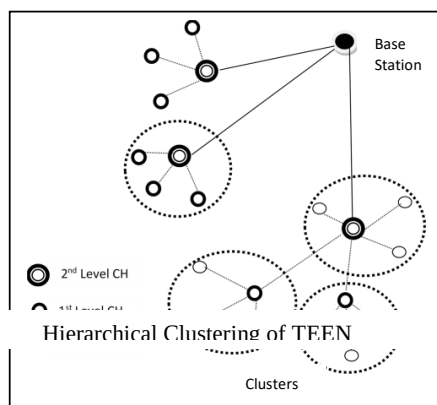
Hard Threshold: This is a threshold value for the sensed attribute. It is the absolute value of the attribute beyond which, the node sensing this value must switch on its transmitter and report to its cluster head.

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

The nodes sense their environment continuously. The first time a parameter from the attribute set reaches its hard threshold value, the node switches on its transmitter and sends the sensed data. The sensed value is stored in an internal variable in the node, called the sensed value(SV).The nodes will next transmit data in the current cluster period, only when both the conditions are true. First the current value of the sensed attribute is greater than the hard threshold. Second the current value of the sensed attribute differs from SV by an amount equal to or greater than the soft threshold.Threshold tries to reduce the

number of transmissions by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The soft threshold further reduces the number of transmissions by eliminating all the transmissions which might have otherwise occurred when there is little or no change in the sensed attribute once the hard threshold.[21]

TEEN is useful for applications where the users can control a trade-off between energy efficiency, data accuracy, and response time dynamically. TEEN uses a data-centric method with hierarchical approach. 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. However, TEEN is not suitable for sensing applications where periodic reports are needed since the user may not get any data at all if the thresholds are not reached.



4.5 APTEEN

APTEEN is Adaptive Periodic Threshold-sensitive Energy Efficient Sensor Network Protocol. In APTEEN once the CHs are decided, in each cluster period, the cluster head first broadcasts the following parameters:

Attributes (A): This is a set of physical parameters which the user is interested in obtaining data about.

Thresholds: This parameter consists of a hard threshold (HT) and a soft threshold (ST). HT is a particular value of an attribute beyond which a node can be triggered to transmit data. ST is a small change in the value of an attribute which can trigger a node to transmit data again.

Schedule: This is a TDMA schedule assigning a slot to each node.

Count Time (TC): It is the maximum time period between two successive reports sent by a node. It can be a multiple of the TDMA schedule length and it accounts for the proactive component

The architecture of APTEEN is same as in TEEN, which uses the concept hierarchical clustering for energy efficient communication between source sensors and the sink. APTEEN supports three different query types namely:

- (i) Historical query, to analyze past data values
- (ii) One-time query, to take a snapshot view of the network
- (iii) Persistent queries, to monitor an event for a period of time.

The main features of APTEEN Protocol are by sending periodic data, it gives the user a complete picture of the network. It also responds immediately to drastic changes, thus making it responsive to time critical situations. It offers a flexibility of allowing the user to set the time interval (TC) and the threshold values for the attributes. Energy consumption can be controlled by the count time and the threshold values. The hybrid network can emulate a proactive network or a reactive network, by suitably setting the count time and the threshold values.

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

6. Conclusion

Routing in Wireless sensor networks is a new area of research, with a limited, but rapidly growing set of research results. In this paper, we presented a survey of routing techniques in wireless sensor networks which have been presented in the literature. They have the common aim of trying to prolong the lifetime of the sensor network, while not compromising data delivery. Due to limited energy resources of sensor nodes, the main challenges in the design of routing protocols in WSNs is energy efficiency. The main objective behind the routing protocol design is to keep the sensors operating for as long as possible, so that the lifetime of wireless sensor network can be increased. The energy consumption of the sensor nodes is dominated by data transmission and reception. The energy efficient hierarchical protocols such as LEACH, PEGASIS, HEED, TEEN, APTEEN are described in this paper that are energy efficient because main aim of such protocols is to efficiently maintain the energy usage of sensor nodes by involving them in multi-hop communication within a particular cluster. This survey can be helpful for designers of WSNs in selection of an appropriate hierarchical routing protocol for a specific application that requires mobile nodes.

Routing Protocols	Classification	Position Awareness	Power Usage	Data Aggregation	QoS	Scalability	Multi path	Query Based
LEACH	Hierarchical	No	Maximum	Yes	No	Good	No	No

PEGASIS	Hierarchical	No	Maximum	No	No	Good	No	No
HEED	Hierarchical	No	Maximum	Yes	No	Good	Yes	No
TEEN	Hierarchical	No	Maximum	Yes	No	Good	No	No
APTEEN	Hierarchical	No	Maximum	Yes	No	Good	No	No

Table 2: Comparison of routing Protocols in WSN

Two issues should be considered in the future research. First issue is the real-work implantations. Simulation of the routing protocols depends on modeling the hardware of the sensor nodes. Second issue is the overheads and computational time of clustering the network. A centralized routing is more energy-efficient than the distributed routing. However in the centralized routing, all sensor nodes should send their information such as their locations and energy to BS. This takes some time and increases the overheads of protocol especially in the dense networks and the BS is far away from the sensor field.

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