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A Survey of Energy-Efficient Hierarchical Cluster-Based Routing in Wireless Sensor Networks

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ABSTRACT

Recent technological advances in communications and computation have enabled the development of low-cost, low-power, small in size, and multifunctional sensor nodes in a wireless sensor network. Since the radio transmission and reception consumes a lot of energy, one of the important issues in wireless sensor network is the inherent limited battery power within network sensor nodes. Therefore, battery power is crucial parameter in the algorithm design to increase lifespan of nodes in the network. In addition to maximizing the lifespan of sensor nodes, it is preferable to distribute the energy dissipated throughout the wireless sensor network in order to maximize overall network performance. Much research has been done in recent years, investigating different aspects like, low power protocols, network establishments, routing protocol, and coverage problems of wireless sensor networks. There are various routing protocols like location-aided, multi-path, data-centric, mobility-based, QoS based, heterogeneity-based, hierarchical routing, hybrid routing, etc., in which optimal routing can be achieved in the context of energy. In this paper, the focus is mainly driven over the survey of the energy-efficient hierarchical cluster-based available routings for Wireless Sensor Network.

Keywords: Wireless Sensor Networks, Cluster Head, Cluster-based routing, Hierarchical clustering, Base Station

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1. INTRODUCTION

Recent technological advances in micro electronic mechanical systems (MEMS) and wireless communication technologies have enabled the development of tiny, low--cost, low-power, and multifunctional smart sensor nodes in a wireless sensor network (WSN). Wireless Sensor Networks (WSNs) have been widely considered as one of the most important technologies for the twenty-first century [27],[29]. These smart sensor nodes are deployed in a physical area and networked through internet and wireless links, which provide unprecedented opportunities for a variety of civilian and military applications, for example, environmental monitoring, battle field surveillance, and industry process control [28]. The development of wireless sensor networks was originally motivated by military applications such as battlefield surveillance. However, wireless sensor networks are now used in many civilian application areas, including environment and habitat monitoring, healthcare applications, home automation, and traffic control.

Distinguished from traditional wireless communication networks, for example, cellular systems and mobile ad hoc networks (MANET), WSNs have unique characteristics such as denser level of node deployment, higher unreliability of sensor nodes, and severe energy, computation, and storage constraints [1], which present many new challenges in the development and application of WSNs. A large amount of research activities have been carried out to explore and solve various design and application issues, and significant advances have been made in the development and deployment of' WSNs.

A WSN typically consists of a large number (tens to thousands) of low-cost, low-power, and multifunctional sensor nodes that are deployed in a region of interest. These sensor nodes are small in size, but are equipped with embedded microprocessors, radio receivers, and power components to enable sensing, computing, communication, and actuation. These components are integrated on a single or multiple boards, and packaged in a few cubic inches. With state-of-the-art, low-power circuit and networking technologies, a sensor node typically powered by 2 AA batteries can last for up to three years with a 1% low duty cycle working mode.

A WSN communicates over a short distance through wireless channels for information sharing and cooperative processing to accomplish a common task. WSNs can be deployed on a global scale for environmental monitoring and habitat study, over a battlefield for military surveillance and reconnaissance, in emergent environments for search and rescue, in factories for condition based maintenance and process control, in buildings for infrastructure health monitoring, in homes to realize smart homes, or even in bodies for patient monitoring.

Figure 1 shows a typical schematic of a wireless sensor network (WSN). After the initial deployment (typically ad hoc), sensor nodes are responsible for self-organizing an appropriate network infrastructure, often with multi-hop connections between sensor nodes. The onboard sensors then start collecting acoustic, seismic, infrared or magnetic information about the environment, using either continuous or event driven working modes. Location and positioning information can also be obtained through the global positioning system (GPS) or local positioning algorithms. This information can be gathered from across the network and appropriately processed to construct a global view of the monitoring phenomena or objects. The basic philosophy behind WSNs is that, while the capability of each individual sensor node is limited, the aggregate power of the entire network is sufficient for the required mission.

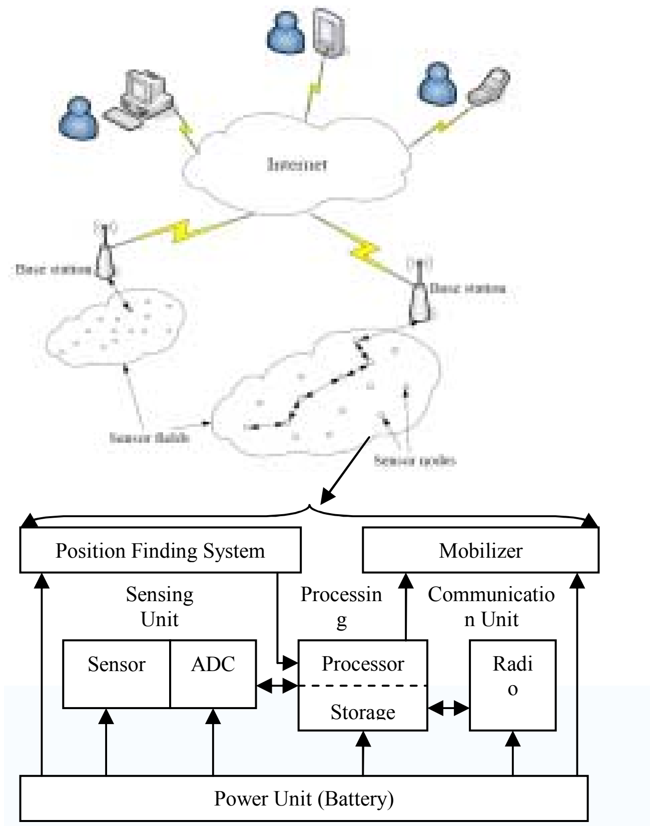

Fig. 1 Schematic of a Wireless Sensor Network Architecture

In a typical scenario, users can retrieve information of interest from a WSN by injecting queries and gathering results from the so-called base stations (or sink nodes), which behave as an interface between users and the network. In this way, WSNs can be considered as a distributed database.

The sensor nodes are densely deployed either inside the sink or very close to it and have limited power, computational capacity and memory. Sensor nodes are very prone to failures. Sensor nodes may not have global identification (ID) because of the large amount of overhead. Sensor nodes are densely deployed in large numbers.

Thus, the fundamental goal of a WSN is to produce information from raw local data obtained (sensed data) by individual sensor mode by prolonging the life time of WSN as much as possible. The resource constrained nature of sensor nodes pose the unique challenges to the design of WSNs for their applications. The limited power of sensor nodes mandates the design of energy-efficient communication protocol.

Routing in sensor networks is very challenging due to several characteristics that distinguish them from contemporary communication and wireless ad-hoc networks

[30]. The sensor nodes are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage and thus require careful resource management. Researchers have devised many protocols for communication, and security in wireless networks life infrastructure based networks, ad-hoc networks, mobile networks, etc. Much research has been done in recent years, investigating different aspects like, low power protocols, network establishments, routing protocol, coverage problems and the establishment of secure wireless sensor networks. A variety of protocols were proposed for prolonging the life of WSN and for routing the correct data to the base station [2], [3], [7], [8], [10], [11], [12], [14], [15], [16], [17], [18], [20], [21], [24], [25], [26]. But each protocol has disadvantages and is not suitable for area monitoring applications. These protocols cannot be used directly due to resource constraints of sensor nodes for resources like limited battery power, communication capability, and computational speed. Even after many efforts, there are still many design options open for improvement, and for further research targeted to the specific applications, need to be done. Therefore, there is a need to study alternate and/or new protocol which enables more efficient use of scarce resources at individual sensor nodes for an application.

There are different routing protocols already reported for WSN applications but mostly they are for static networks. All major protocols may be categorized into four categories as shown in Table 1.

Table 1: Categories of Routing Protocols

Category	*Representative Protocols*
Data Centric Protocols	Flooding and Gossiping, SPIN, Directed Diffusion, Rumor Routing, Gradient Based Routing, Energy-aware Routing, CADR, COUGAR & ACQUIRE.
Hierarchical Protocols	LEACH, PEGASIS, H-PEGASIS, TEEN & APTEEN
Location Based Protocols	MECN & SMECN, GAF & GEAR
Network Flow & QoS Aware Protocol	Maximum Lifetime Energy Routing, Maximum Lifetime Data Gathering, Minimum Cost Forwarding, SAR & SPEED

In this paper various energy-efficient hierarchical cluster-based routing protocols for wireless sensor network are discussed and compared. The paper is organized in the following way. In Section 2, the energy-efficient clustering structures in WSN are briefly explained. In Sections 3, the energy-efficient cluster-based routing protocols are discussed. In Section 4, various energy-efficient hierarchical cluster routing protocols are discussed and compared. Finally, Section 5 concludes the survey.

2. ENERGY-EFFICIENT CLUSTERING STRUCTURES IN WSN

Traditional (or flat) routing protocols for WSN may not be optimal in terms of energy consumption. Clustering can be used as an energy-efficient communication protocol. The objectives of clustering are to minimize the total transmission power aggregated over the nodes in the selected path, and to balance the load among the nodes for prolonging the network lifetime. Clustering is a sample of layered protocols in which a network is composed of several clumps (or clusters) of sensors. As shown in Figure 2, each clump or cluster is managed by a special node or leader, called cluster head (CH), which is responsible for coordinating the data transmission activities of all sensors in its clump. All sensors in a cluster communicate with a cluster head that acts as a local coordinator or sink for performing intra-transmission arrangement and data aggregation. Cluster heads in tern transmits the sensed data to the global sink. The transmission distance over which the sensors send their data to their cluster head is smaller compared to their respective distances to the global sink. Since a network is characterized by its limited wireless channel bandwidth, it would be beneficial if the amount of data transmitted to the sink can be reduced. To achieve this goal, a local collaboration between the sensors in a cluster is required in order to reduce bandwidth demands.

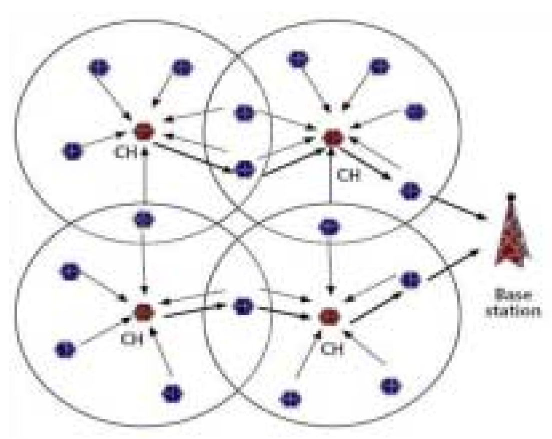

Figure 2 Clustering of Sensor Nodes

As shown in Figure 2, clustering usually localizes the routing setup within the cluster and therefore it reduces the routing overhead by each node and the topology maintenance overhead. Using clustering, the network appears smaller and more stable. The information, generated from neighboring sensor nodes, is often redundant and highly correlated, so data aggregation by each cluster head conserves communication bandwidth as well. Moreover, the ability to use different power levels in inter-cluster and intra cluster communication reduces the interferences and the collisions in the network resulting in a better throughput. Clustering is a challenging task. CHs often lose more energy compared to regular nodes. It is necessary to perform re-clustering periodically in order to select energy-abundant nodes to serve as CHs, thus distributing the load uniformly on all the nodes.

2.1 Cluster-based Hierarchical Model

As shown in Figure 3, a hierarchical approach breaks the network into clustered layers [37]. Nodes are grouped into clusters with a cluster head that has the responsibility of routing from the cluster to the other cluster heads or base stations. Data travel from a lower clustered layer to a higher one. Although, it hops from one node to another, but as it hops from one layer to another it covers larger distances. This moves the data faster to the base station. Theoretically, the latency in such a model is much less than in the multi-hop model. Clustering provides inherent optimization capabilities at the cluster heads. In the cluster-based hierarchical model, data is first aggregated in the cluster then sent to a higher-level cluster-head. As it moves from a lower level to a higher one, it travels greater distances, thus reducing the travel time and latency. This model is better than the one hop or multi-hop model.

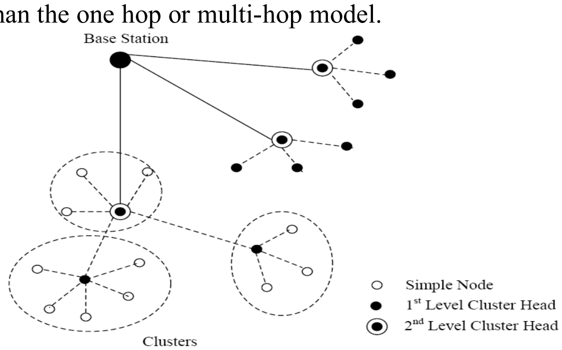

Figure 3 Cluster-based Hierarchical Model

A cluster-based hierarchy moves the data faster to the base station thus reducing latency than in the multi-hop model. Further, in cluster-based model only cluster-heads performs data aggregation whereas in the multi-hop model every intermediate node performs data aggregation. As a result, the cluster-based model is more suitable for time-critical applications than the multi-hop model. However, it has one drawback, namely, as the distance between clustering level increases, the energy spent is proportional to the square of the distance. This increases energy expenditure. Despite this drawback, the benefits of this model far outweigh its drawback. A cluster-based hierarchical model offers a better approach to routing for WSNs.

3. ENERGY-EFFICIENT CLUSTER-BASED ROUTING PROTOCOL IN WSN

Clustering algorithms for traditional wireless ad hoc networks are not well suited for the unique features and application requirements of WSNs [29]. Some of the special features of WSNs are as follows:

- The number of sensors nodes in a WSN is in hundreds of thousands and are limited in power, computational capacities, and storage memory.
- Sensor nodes are densely deployed.
- Sensor nodes are prone to failure.
- The topology of a WSN may change rather frequently because a sensor node may alternate between the active and sleep states.
- Sensor nodes may not have global identification (ID) because of the large amount of overhead and the large number of sensors.

Since a large number of sensor nodes are densely deployed, multi-hop communications are prone to occur in WSNs [31], [32], [33], [34]. As compared to traditional ad hoc networks, the transmission power levels can be kept low, and the communications consume less power in WSNs. As discussed in section 2, one approach is to cluster a WSN into clusters such that all members of the clusters are directly connected to the cluster heads (CHs). Sensor nodes in the same cluster can communicate directly with their CH without any intermediate sensor nodes. CHs can transmit gathered information back to the base station through multi-hop communication among CHs. A D number of multi-hop (D-hop) clusters may be defined as a cluster with all the sensor nodes in the cluster reachable by a path with path length $\leq D$ hopes [35]. It is very important to determine an optimal value of D that minimizes the overall energy consumption in a WSN. To design an optical mechanism, various factors must be considered such as (i) the data packet size, (ii) frequency of transmissions, (iii) maximum allowable latency, (iv) local computation processes, and (v) maintenance of partial database information.

As discussed in previous sections, clustering of sensor nodes not only allows aggregation of sensed information, but also minimizes the energy consumed within individual clusters and reduces both the traffic and contention for channel clustering. Thus, exploiting the trade-offs among energy, accuracy, and latency, and using hierarchical architectures are important techniques for prolonging the network lifetime.

4. ENERGY-EFFICIENT HIERARCHICAL CLUSTER ROUTING ALGORITHMS

As discussed in [29], energy-efficient hierarchical clustering (EEHC) is a distributed randomized clustering algorithm that maximizes the lifetime of a network with a large number of sensor nodes [35]. The EEHC algorithm organizes the sensors in a network into clusters with a hierarchy of cluster heads (CHs). The CHs collect the information from the sensor nodes within their clusters and send an aggregated report through the hierarchy of cluster heads to the base station. The EEHC algorithm assumes that communication environment is contention and error free. The energy consumed in network will depend on (i) the probabilities of each sensor node becoming a cluster head at each level in the hierarchy and (ii) the maximum number of hops allowed between one cluster node and its CH. The optimal clustering parameters are obtained through hierarchical clustering to minimize the total energy consumption in the network. However, CHs in hierarchical model consume relatively more energy than other sensor nodes because CHs have more loads to handle. Hence, CHs may run out of their energy faster than other sensor nodes. Thus, the EEHC algorithm can be run periodically for load balancing or triggered as the energy levels of the CHs fall below a certain threshold.

Many research projects in the last few years have explored hierarchical clustering in WSN from different perspectives. A variety of protocols have been proposed for prolonging the life of WSN and for routing the correct data to the base station. Each protocol has advantages and disadvantages. Battery power of individual sensor nodes is a precious resource in the WSN [4], [5]. Some of the hierarchical protocols are LEACH, PEGASIS, TEEN, and APTEEN.

Low-energy adaptive clustering hierarchy (LEACH): LEACH [3], [7] is the first and most popular energy-efficient hierarchical clustering algorithm for WSNs that was proposed for reducing power consumption. In LEACH, the clustering task is rotated among the nodes, based on duration. Direct communication is used by each CH to forward the data to the base station (BS). It is an application-specific data dissemination protocol that uses clusters to prolong the life of the wireless sensor network. LEACH is based on an *aggregation* (or *fusion)* technique that combines or aggregates the original data into a smaller size of data that carry only mean-ingful information to all individual sensors. LEACH divides the a network into several cluster of sensors, which are constructed by using localized coordination and control not only to reduce the amount of data that are transmitted to the sink, but also to make routing and data dissemination more scalable and robust. Given that energy dissipation of the sensor depends on the distance and the data size to be transmitted, LEACH attempts to transmit data over short distances and reduce the number of transmission and reception operations. The key features of LEACH are: (i) randomized rotation of the CH and corresponding clusters, (ii) local compression to reduce global communication, (iii) and localized coordination and control for cluster set-up and operation.

LEACH uses a randomize rotation of high-energy CH position rather than selecting in static manner, to give a chance to all sensors to act as CHs and avoid the battery depletion of an individual sensor and dieing quickly. The operation of LEACH is divided into rounds, each of which has mainly two phases namely (i) a setup phase to organize the network into clusters, CH advertisement, and transmission schedule creation and (ii) a steady-state phase for data aggregation, compression, and transmission to the sink. Cluster heads (CHs) use CSMA MAC protocol to advertise their status. Thus, all non-cluster head sensors must keep their receivers ON during the setup phase in order to hear the advertisements sent by the CHs. These CHs are selected with some probability by themselves and broadcast their statuses to the other sensors in the network. The decision for a sensor to become a CH is made independently without any negotiation with the other sensors. Specifically, a sensor decides to become a CH based on the desired percentage *P* of CHs (determined *a priori*), the current round, and the set of sensors that have nor become CH in the past *1/P* rounds. If the number of CHs <*T(n)*, a sensor *n* becomes a CH for the current round, where *T(n)* is a threshold given by

$$T(n) = \begin{cases} \frac{P}{1-P*(r \, mod \frac{1}{P})} & \text{if n} \in \text{G} \\ 0 & \text{otherwise} \end{cases}$$

where *P* is the desired percentage of cluster heads, *r* is the current round, and *G* is the set of nodes that have been cluster- heads (CHs) in the last *1/P* rounds. The sensor nodes that are CHs in round ‘0’ cannot be a CH for the next *1/P–1* rounds. Once the network is divided into clusters, a CH computes a TDMA schedule for its sensors specifying when a sensor in the cluster is allowed to send its data. Thus, a sensor will turns its radio ON only when it is authorized to transmit according to the schedule established by its cluster head, therefore yielding significant energy savings. Furthermore, LEACH enables data fusion in each cluster by aggregating the data in order to reduce the total amount of data and then sends them to the sink. The sensors within a cluster transmit their sensed data over short distances, whereas CHs communicate directly with the sink.

LEACH achieves over a factor of 7x and 8x reduction in energy dissipation compared to direct communication and a factor of 4x and 8x compared to the minimum transmission energy (MTE) routing protocol. The nodes die randomly and dynamic clustering increases system lifetime in case of LEACH as compared to direct transmission, MTE routing, and static clustering. LEACH is completely distributed and requires no global knowledge of network.

LEACH reduces energy consumption by (a) minimizing the communication cost between sensors and their cluster heads and (b) turning off non-head nodes as much as possible [38]. It has major characteristics such as (i) it rotates the cluster heads in a randomized fashion to achieve balanced energy consumption, (ii) sensors have synchronized clocks so that they know the beginning of a new cycle, (iii) sensors do not need to know location or distance information, (iv) the time duration of the set-up phase is non-deterministic, and if the duration is too long due to collisions, sensing services are interrupted. In such cases, LEACH may be unstable during the set-up phase depending on the density of sensors.

LEACH uses single-hop routing where each node can transmit directly to the cluster-head and the sink. Therefore, it is not applicable to networks deployed in large regions. Furthermore, the idea of dynamic clustering brings extra overhead, e.g. head changes, advertisements etc., which may diminish the gain in energy consumption. While LEACH helps the sensors within their cluster dissipate their energy slowly, the CHs consume a larger amount of energy when they are located farther away from the sink. Also, LEACH clustering terminates in a finite number of iterations, but does not guarantee good CH distribution and assumes uniform energy consumption for CHs.

Enhanced Low-Energy Adaptive Clustering Hierarchy (E-LEACH): E-LEACH [7] further improved LEACH in two major aspects. E-LEACH proposes a cluster head selection algorithm for sensor networks that have non-uniform starting energy level among the sensors. However, this algorithm assumes that sensors have global information about other sensors' remaining energy. E-LEACH also determines that, under certain assumptions, the required number of cluster heads has to scale as the square root of the total number of sensor nodes to minimize the total energy consumption. Other aspects of E-LEACH are the same as LEACH.

LEACH-Centralized (LEACHC): LEACH-C uses a centralized clustering algorithm and same steady-state protocol. During the set-up phase of LEACH-C, each node sends information about current location and energy level to base station (BS). The BS will determine clusters, CH node and non-CH nodes of each cluster. The BS utilizes its global information of the network to produce better clusters that require less energy for data transmission. The number of CHs in each round of LEACH-C equals a predetermined optimal value, whereas for LEACH the number of CHs varies from round due to the lack of global coordination among nodes.

Multi-hop LEACH (M-LEACH): M-LEACH [39] modifies LEACH allowing sensor nodes to use multi-hop communication within the cluster in order to increase the energy efficiency of the protocol. Other works define special nodes (called gateways) that are able to send the information generated inside the cluster directly to the sink [40]. This work extends the existing solutions by allowing multi-hop inter-cluster communication in sparse WSNs in which the direct communication between CHs or the sink is not possible due to the distance between them. Thus, the main innovation of the solution proposed here is that the multi-hop approach is followed inside the cluster (messages from sensor nodes to the CH) and outside the cluster (from CHs to the sink using intermediate sensor nodes). CHs can also perform data fusion to the data receive, allowing a reduction in the total transmitted and forwarded data in the network.

LEACH with Fixed Cluster (LEACH-F): LEACH-F [42] is the further development of LEACH, which is based on clusters that are formed once and then fixed. Then, the cluster head position rotates among the nodes within the cluster. The advantage with this is that, once the clusters are formed, there is no set-up overhead at the beginning of each round. To decide clusters, LEACH-F uses the same centralized cluster formation algorithm as LEACH-C. The fixed clusters in LEACH-F do not allow new nodes to be added to the system and do not adjust their behavior based on nodes dying.

Power-Efficient Gathering in Sensor Information Systems (PEGASIS): PEGASIS [41] is an extension of the LEACH protocol, which rather forming multiple clusters, forms chains from sensor nodes so that each node transmits and receives from a neighbor and only one node is selected from that chain to transmit to the base station (sink). The data is gathered and moves from node to node, aggregated and eventually sent to the base station. The chain construction is performed in a greedy way. Unlike LEACH, PEGASIS avoids cluster formation and uses only one node in a chain to transmit to the BS (sink) instead of using multiple nodes. A sensor transmits to its local neighbors in the data fusion phase instead of sending directly to its CH as in the case of LEACH. In PEGASIS routing protocol, the construction phase assumes that all the sensors have global knowledge about the network, particularly, the positions of the sensors, and use a greedy approach. Specifically, it starts with the furthest sensor to sink to guarantee that sensors farther away from the sink have close neighbors. When a sensor fails or dies due to low battery power, the chain is constructed using the same greedy approach by bypassing the failed sensor. In each round, a randomly chosen sensor node from the chain will transmit the aggregated data to the BS, thus reducing the per round energy expenditure compared to LEACH.

Thus, 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 BS. To locate the closest neighbor node in PEGASIS, each node uses the signal strength to measure the distance to all neighboring nodes and then adjusts the signal strength so that only one node can be heard. When the round of all nodes communicating with the BS 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.

The objectives of PEGASIS routing protocol are (i) to increase the lifetime of each node by using collaborative techniques, and (ii) allow only local coordination between nodes are close together so that the bandwidth consumed in communication is reduced. 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. Such performance gain is achieved through the elimination of the overhead caused by dynamic cluster formation in LEACH and through decreasing the number of transmissions and reception by using data aggregation. 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. In practical cases, sensor nodes use multi-hop communication to reach the BS. Also, PEGASIS assumes that all nodes maintain a complete database about the location of all other nodes in the network. The method of which the node locations are obtained is not outlined. In addition, PEGASIS assumes that all sensor nodes have the same level of energy and they are likely to die at the same time. 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.

Hierarchical PEGASIS: An extension to PEGASIS, called Hierarchical-PEGASIS was introduced in [43] 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 incorporate signal coding and spatial transmissions. H-PEGASIS proposes a solution to the data gathering problem by considering energy × delay metric. In order to reduce the delay in PEGASIS, simultaneous transmissions of data messages are pursued. To avoid collisions and possible signal interference among the sensors, two approaches have been investigated. The first approach incorporates signal coding, e.g. CDMA. In the second approach 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.

Energy Balancing PEGASIS (EB-PEGASIS): EB-PEGASIS [44] is an energy efficient chaining algorithm in which a node will consider average distance of formed chain. If the distance from closest node to its upstream node is longer than distance thresh (the distance thresh can obtain from average distance of formed chain), the closest node is a "far node". If the closest node joins the chain, it will emerge a "long chain". In this condition, the "far node" will search a nearer node on formed chain. Through this method, the new protocol EB-PEGASIS can avoid "long chain" effectively. EB-PEGASIS can guarantee approximately the same in consumed energy of sensor nodes, and avoid the dying of some nodes early than other nodes to prolong the lifetime of sensor networks. It not only save energy on sensors, but also balance the energy consumption of all sensor nodes.

Hybrid, Energy-Efficient Distributed Clustering (HEED): HEED [25], [26] 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, and (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.

In HEED, the clustering process at each sensor node requires several rounds. Every round is long enough to receive messages from any neighbor within the cluster range [29]. As in LEACH, an initial percentage of CHs in the network C_{prob}, is predefined. The parameter C_{prob} is only used to limit the initial CH announcements and has no direct impact on the final cluster structure. In HEED, each sensor node sets the probability CH_{prob} of becoming a CH as follows

$$CH_{prob} = C_{prob} \cdot \frac{E_{residual}}{E_{\max}}$$

where $E_{residual}$ is the estimated current residual energy in this sensor node and E_{max} is the maximum energy corresponding to a fully charged battery, which is typically identical for homogeneous sensor nodes. The CH_{prob} value must be greater than a minimum threshold p_{min}. A CH is either a tentative CH, if its CH_{prob} is <1, or a final CH, if its CH_{prob} has reached 1.During each round of HEED, every sensor node that never heard from a CH elects itself to become a CH with probability CH_{prob}. The newly selected CHs are added to the current set of CHs. If a sensor node is selected to become a CH, it broadcasts an announcement message as a tentative CH or a final CH. A sensor node hearing the CH list selects the CH with the lowest cost from this set of CHs. Every node then doubles its CH_{prob} and goes to the next step. If a node completes the HEED execution without electing itself to become a CH or joining a cluster, it announces itself as a final CH. A tentative CH node can become a regular node at a later iteration if it hears from a lower cost CH. Here, a node can be selected as a CH at consecutive clustering intervals if it has higher residual energy with lower cost.

In HEED, the distribution of energy consumption extends the lifetime of all the nodes in the network, thus sustaining stability of the neighbor set. Nodes also automatically update their neighbor sets in multi-hop networks by periodically sending and receiving messages. 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.

Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN): TEEN [45], [46] 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. Thus, the sensor network architecture in TEEN is based on a hierarchical grouping where closer nodes form clusters and this process goes on the second level until the BS (sink) is reached. The model is similar to the architecture as depicted in Figure 3. 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.

TEEN is a clustering communication protocol that targets a reactive network and enables CHs to impose a constraint on when the sensor should report their sensed data. After the clusters are formed, the CH broadcasts two thresholds to the nodes namely (i) shard threshold (H_T), and (ii) soft threshold (S_T). Hard threshold is the minimum possible value of an attribute, beyond which a sensor should turn its transmitter ON to report its sensed data to its CH. Thus, the hard threshold allows the nodes to transmit only when the sensed attribute is in the range of interest, thus reducing the number of transmissions significantly. Once a node senses a value at or beyond the hard threshold, it transmits data only when the value of that attribute changes by an amount equal to or greater than the soft threshold, which indicates a small change in the value of the sensed attribute and triggers a sensor to turn ON its transmitter and send its sensed data to the CH. As a consequence, soft threshold will further reduce the number of transmissions for sensed data if there is little or no change in the value of sensed attribute. Thus, the sensors will send only sensed data that are of interest to the end user based on the hard threshold value and the change with respect to the previously reported data, thus yielding more energy savings. One can adjust both hard and soft threshold values in order to control the number of packet transmissions. However, both values of hard and soft thresholds have an impact on TEEN. These values should be set very carefully to keep the sensors responsive by reporting sensed data to the sink.

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. 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.

Adaptive Threshold Sensitive Energy Efficient Sensor Network Protocol (APTEEN): APTEEN [47] is an improvement to TEEN to overcome its shortcomings and aims at both capturing periodic data collections (LEACH) and reacting to time-critical events (TEEN). Thus, APTEEN is a hybrid clustering-based routing protocol that allows the sensor to send their sensed data periodically and react to any sudden change in the value of the sensed attribute by reporting the corresponding values to their CHs. 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. When the base station forms the clusters, the CHs broadcast the attributes, the hard and soft threshold values, and TDMA transmission schedule to all nodes, and a maximum time interval between two successive reports sent to a sensor, called count time (T_C). CHs also perform data aggregation in order to save energy. 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; and (iii) persistent queries, to monitor an event for a period of time.

APTEEN guarantees lower energy dissipation and a larger number of sensor alive [47]. Simulation of TEEN and APTEEN has shown them to outperform LEACH [3]. Experiments have demonstrated that APTEEN's performance is between LEACH and TEEN in terms of energy dissipation and network lifetime. While in LEACH sensors transmit their sensed data continuously to the sink, in APTEEN sensors transmit their sensed data based on the threshold values. TEEN gives the best performance since it decreases the number of transmissions. The main drawbacks of the two approaches are the overhead and complexity of forming clusters in multiple levels, implementing threshold-based functions and dealing with attribute-based naming of queries.

5. CONCLUSION AND FUTURE RESEARCH

Due to the scarce energy resources of sensors, energy efficiency is one of the main challenges in the design of protocols for WSNs. The ultimate objective behind the protocol design is to keep the sensors operating for as long as possible, thus extending the network lifetime. In this paper we have surveyed and summarized recent research works focused mainly on the energy efficient hierarchical cluster-based routing protocols for WSNs. As this is a broad area, this paper has covered only few sample of routing protocols. The protocols discussed in this paper have individual advantages and pitfalls. Based on the topology, the protocol and routing strategies can be applied. The factors affecting cluster formation and CH communication are open issues for future research. Moreover, the process of data aggregation and fusion among clusters is also an interesting problem to explore.

For realization of sensor networks, it is needed to satisfy the constraints introduced by factors such as fault tolerance, scalability, cost, topology change, environment, and power consumption. Since these constraints are highly stringent and specific for sensor networks, new wireless ad hoc networking techniques are required to be explored further. Though the performance of the protocols discussed in this paper is promising in terms of energy efficiency, further research would be needed to address issues related to Quality of Service (QoS) posed by video and imaging sensors and real-time applications.

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