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Clustering Routing Algorithms In Wireless Sensor Networks: An Overview

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Abstract

Wireless sensor networks (WSNs) are becoming increasingly attractive for a variety of applications and have become a hot research area. Routing is a key technology in WSNs and can be coarsely divided into two categories: flat routing and hierarchical routing. In a flat topology, all nodes perform the same task and have the same functionality in the network. In contrast, nodes in a hierarchical topology perform different tasks in WSNs and are typically organized into lots of clusters according to specific requirements or metrics. Owing to a variety of advantages, clustering routing protocols are becoming an active branch of routing technology in WSNs. In this paper, we present an overview on clustering routing algorithms for WSNs with focus on differentiating them according to diverse cluster shapes. We outline the main advantages of clustering and discuss the classification of clustering routing protocols in WSNs. In particular, we systematically analyze the typical clustering routing protocols in WSNs and compare the different approaches based on various metrics. Finally, we conclude the paper with some open questions.

Keywords: WSN, clustering routing, block-based clustering, grid-based clustering, chain-based clustering

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1. Introduction

Recent advances in micro-electro-mechanical system technology and wireless communication technology make it feasible to mass produce small sensor nodes with sensing, computation, and communication capabilities. This has spurred a substantial amount of research on wireless sensor networks (WSNs) over the past few years. WSNs have wide application areas, such as military reconnaissance, disaster management, security surveillance, habitat monitoring, medical and health, industrial automation, and etc. [1][2][3]. Typically, a WSN is composed of a large number of tiny sensor nodes distributed over a large area with one or more powerful sink nodes collecting information from other nodes. All sensor nodes are with limited power supply and have the capabilities of information sensing, data processing and wireless communication. In order to preserve energy, the scheme of low duty cycling should be adopted in WSNs. Moreover, intra-network data processing such as data aggregation and fusion helps to reduce the number of messages, which are finally sent to the sink or base station.

As one of the key technologies, routing is full of challenges in WSNs, mainly due to the limit of power supply, processing capability, transmission bandwidth, and etc. According to network structure, routing algorithms in WSNs can be coarsely grouped into two types: flat routing and hierarchical routing. In a flat topology, all nodes execute the same tasks and have the same functionalities in the network. Moreover, information dissemination is performed hop by hop generally using the flooding method. The popular flat routings in WSNs include Flooding and Gossiping [4], SPIN [5], DD [6], Rumor [7], GPSR [8], TBF [9], EAR [10], GBR [11], SAR [12], and etc. These flat routing algorithms are relatively effective in small-scale networks. However, it is relatively undesirable in large-scale networks because the resources are limited and more data processing and bandwidth are needed. On the other hand, in a hierarchical topology, nodes execute different tasks in WSNs and typically are grouped into lots of clusters on the basis of specific requirements or metrics. As a rule, a cluster covers a leader, named cluster head, and member nodes. Besides, cluster heads can be grouped into further hierarchical levels. Generally, nodes with higher energy act as cluster heads and perform the task of data processing and information dissemination, while nodes with lower energy act as member nodes and perform the task of information sensing. The popular clustering routings algorithms in WSNs include LEACH [13], HEED [14], DWEHC [15], UCS [16], EECS [17], TEEN [18], BCDCP [19], GAF [20], PANEL [21], TTDD [22], HGMR [23], PEGASIS [24], CCS [25], TSC [26], and etc. Clustering routing algorithms are becoming an active branch of routing technology in WSNs on account of a variety of advantages, such as more scalable, less load, less energy consumption and more robust.

A variety of clustering routing algorithms in WSNs have been proposed in the current literatures. These routing protocols have taken into consideration the inherent characteristics of WSNs along with the application and architecture requirements. In this paper, we explore these clustering routing techniques in WSNs that have been proposed in recent years and develop a classification for these algorithms. Then we discuss each of the routing algorithms under this classification. Our objective is to provide deeper understanding of the current clustering routing algorithms in WSNs and identify some open issues that can be further pursued. To the best of our knowledge, this paper is the first attempt at a relatively comprehensive and systematical overview on clustering routing algorithms in WSNs with focus on differentiating them according to diverse cluster shapes.

The rest of this paper is organized as follows. In Section 2, we outline the advantages of clustering routing algorithms in WSNs. In Section 3, we discuss the classification of clustering routing protocols in WSNs. Especially, we systematically analyze the typical clustering routing algorithms in WSNs in Section 4. We also compare these different protocols in Section 5. Finally, Section 6 concludes the paper with some open issues.

2. Main Advantages of Clustering Routing Algorithms in WSNs

There exist various advantages in clustering routing algorithms compared with flat routing ones in WSNs. The main advantages of clustering routing algorithms are surveyed as follows.

Increase of Scalability: in clustering routing scheme, sensor nodes are divided into a variety of clusters with different assignment levels. The cluster heads are responsible for data aggregation, information dissemination and network management, and the member nodes for events sensing and information collecting in their surroundings. Clustering topology can localize the route set up within the cluster and thus reduce the size of the routing table stored at the individual sensor nodes. Compared with flat topology, this kind of network topology is easier for management, and more scalable to respond to events in the environment [28][29].

Decrease of Load: for clustering topology, all cluster members only send data to cluster heads, and data aggregation is performed at the cluster heads, which help to dramatically reduce transmission data and save energy. In addition, the routes are set up within the clusters which thus reduce the size of the routing table stored at the individual sensor nodes [28][29].

Enhancement of robustness: compared with flat routing method, clustering routing scheme makes it more convenient for network topology control and responding to network changes comprising node increasing, node mobility and unpredicted failures, and etc. Clustering routing scheme only needs to cope with these changes within individual clusters, thus the entire network is more robust and more convenient for management.

Alleviation of Collisions: in clustering routing scheme, a WSN is grouped into clusters and data communications between sensor nodes comprise two modes, i.e. intra-cluster and inter-cluster, respectively for data collection and for information dissemination. The fact that only cluster heads perform the task of information dissemination out of the cluster helps avoiding collisions between sensor nodes, because less nodes share the communication channel with the others in clustering routing scheme.

Reduction of Delay: In flat routing WSNs, data transmission is performed hop by hop usually using the method of flooding. In contrast, in clustering based WSNs, only cluster heads perform the task of data transmissions from one cluster to another one. This helps decreasing the hops from data source to the base station, accordingly it reduces the delay.

3. The Classification of Clustering Routing Algorithms in WSNs

There are a variety of methods to classify clustering routing algorithms in WSNs as follows.

Based on the emphases of the clustering algorithms, clustering routing algorithms in WSNs can be classified into three classes: cluster head election based, cluster formation based and data transmission based algorithms, respectively with the main idea of cluster head election, cluster formation and data transmission.

In the light of the cluster sizes, clustering routing algorithms in WSNs can be grouped into two groups: even and uneven clustering algorithms, respectively with the same size clusters and different size clusters in the network.

One the basis of control manners of clustering, clustering routing algorithms in WSNs can be categorized into centralized, distributed and hybrid approaches. Centralized approaches require global information of the network topology. However, distributed approaches are more scalable because every node is able to take the initiative to become a cluster or a member node without global topology information. Hybrid approaches require a part of global information of the network topology.

According to the intra-cluster routing manners, clustering routing algorithms in WSNs comprise two types: intra-cluster single-hop and intra-cluster multiple-hop clustering routing algorithms.

Clustering routing algorithms in WSNs include two classes: inter-cluster single-hop and inter-cluster multiple-hop clustering routing algorithms according to the inter-cluster routing manners.

Considering the making-decisions manners of nodes, clustering routing algorithms in WSNs can be classified into two classes: probabilistic or iterative. In probabilistic clustering manner, every node can independently decide on its own roles while keeping the message overhead low. Nevertheless, every node must wait for a specific event to occur or certain nodes to decide their roles before making a decision in iterative clustering manner.

Based on convergence time, clustering routing in WSNs include variable and constant convergence time algorithms. The former algorithms accommodate well to small-scale networks in that they have a convergence time which depends on the number of nodes in the network. After a fixed number of iterations, the latter algorithms certainly converge regardless of the scale of the networks.

On the basis of the nature of the deployed sensor nodes, clustering approaches can also be classified into homogeneous or heterogeneous. In the former scenes, the cluster heads are designated at random or according to several criteria. In the latter scenes, the cluster heads are assigned beforehand according to a few factors, such as energy and the capability of computation and communication. In general, even in homogeneous scenes, heterogeneity may occur simply in the light of available energy at nodes, in that a part of nodes in the network will consume more energy as time goes on.

According to how the source sends a route to the base station, clustering approaches can be grouped into three groups, namely, proactive, reactive, and hybrid approaches. In proactive approaches, all routes are computed before they are really needed, while in reactive algorithms, routes are computed on demand. Hybrid approaches use a combination of the above two ideas.

Based on the shapes of the clusters, clustering routing in WSNs can be categorized into three categories: block-based clustering routing, grid-based clustering routing and chain-based clustering routing. In this paper, we discuss clustering routing algorithms in WSNs under this kind of classification.

4. Typical Clustering Routing Algorithms in WSNs

4.1 Block-based Clustering Routing Algorithms

4.1.1 LEACH

Low-Energy Adaptive Clustering Hierarchy (LEACH) [13] is one of the first clustering routing approaches in WSNs. The basic idea of LEACH is an inspiration for many subsequent clustering routing algorithms. The main goal of LEACH is to form clusters based on the received signal strength and elect local cluster heads which act as routers and forward data to the sink.

LEACH randomly selects a few sensor nodes as cluster heads and rotates this role to evenly distribute the energy consumption among the nodes in the network. In this clustering routing scheme, cluster heads compress data arriving from nodes that belong to the respective cluster, and send an aggregated or fused packet to the base station in order to reduce the amount of information to be deliver. Based on clustering, much energy can be saved since data diffusion only be performed by cluster heads rather than all nodes. In LEACH, the optimal number of cluster heads is estimated to be 5% of the total number of nodes. Cluster heads change randomly over time in order to balance energy consumption among all nodes. This decision is made by using a random number between 0 and 1. The node becomes a cluster head for the current round if the number is less than the following threshold:

$$T(n)=\begin{cases}\dfrac{P}{1-P\left(r \bmod \dfrac{1}{P}\right)}, & \text{if } n\in G\\ 0, & \text{otherwise}\end{cases} \tag{1}$$

where P is the desired percentage of cluster heads, r is the current round, and G is the set of nodes that have not been elected cluster heads in the last $1/P$ rounds. When a node is elected a cluster head successfully, it broadcasts an advertisement message to other nodes. According to the received signal strength of the advertisement, other nodes decide which cluster it will join for this round and send a membership message to this cluster head. Data collection in a cluster is centralized with a determinate period using a TDMA schedule created by each cluster head, and all member nodes send data to the cluster heads according to the schedule. After the schedule, the cluster head fuses all the received data and transmits it to the sink directly. **Fig. 1** showed the basic topology of LEACH.

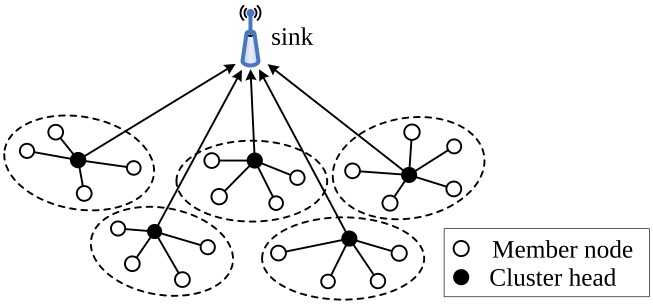

Fig. 1. The basic topology of LEACH

LEACH is a completely distributed approach and requires no global information of network. This approach can optimize energy by shutting down radios of sensor nodes and achieve load balancing to some extent. However, there obviously exist a few drawbacks in LEACH. Firstly, due to one-hop intra and inter cluster topology, LEACH is not applicable to large-scope networks. Cluster heads are assumed to have a long communication range, so this algorithm can breed much energy consumption [32]. Secondly, cluster heads are elected in terms of probabilities without energy considerations, thus LEACH, can easily lead to energy-consumption unbalance. Finally, dynamic clustering may bring about extra overhead and energy consumption in virtue of information advertisements at the beginning of each round.

4.1.2 HEED

Hybrid Energy-Efficient Distributed clustering (HEED) [14] is a multi-hop clustering algorithm in WSNs and can provide an energy-efficient routing with explicit consideration of energy. In HEED, elected cluster heads have relatively high average residual energy compared to member nodes. Additionally, an important goal of HEED is to achieve even-distributed cluster heads throughout the networks.

In HEED, cluster heads are periodically elected based on residual energy and intra-cluster communication cost of the candidate nodes. Initially, a percentage of cluster heads among all nodes, C_{prob}, is set to assume that an optimal percentage cannot be computed a priori. The probability that a node becomes a cluster head is

$$CH_{\text{prob}} = C_{\text{prob}} \frac{E_{\text{residual}}}{E_{\max}} \tag{2}$$

where $E_{\text{residual}}$is the estimated current energy of the node, and $E_{\max}$ is a reference of the maximum energy, which is typically identical for all nodes in the network. The value of CH_{prob}, however, is not allowed to fall below a certain threshold that is selected to be inversely proportional to $E_{\max}$. Afterwards, each node goes through several iterations until it finds the cluster head. If a node cannot find any cluster head, it elects itself to be a cluster head and sends an announcement message to its neighbors. Each node doubles its CH_{prob} value and goes to the next iteration until its CH_{prob} reaches 1. Therefore, there are two types of status that a sensor node could announce to its neighbors: tentative status and final ones. If its CH_{prob} is less than 1, the node becomes a tentative cluster head and can change its status to a regular node at a later iteration if it finds a lower cost cluster head. If its CH_{prob} has reached 1, the node permanently becomes a cluster head.

Due to multi-hop inter-cluster routing rather than long-range communications directly from cluster heads to the sink, HEED outperforms LEACH with respect to the network lifetime, hence it is applicable to large-scope networks. In HEED, the clustering process can be terminated within a constant number of iterations and cluster heads are relatively evenly distributed in the network to some extent [30]. However, there are some problems to be considered in HEED. Firstly, the scheme of cluster head election in terms of probabilities can not realize real even distribution of cluster heads in the network. In HEED, distributing cluster heads evenly in the network is one important goal in order to realize load balancing and hence longer the network lifetime. Moreover, HEED suffers from a consequent overhead since it needs several iterations to form clusters and a lot of packets are broadcast at each iteration. Finally, some cluster heads, especially near the sink, may die earlier, and the hot spot will come into being in the network [31].

4.1.3 DWEHC

Distributed Weight-based Energy-efficient Hierarchical Clustering protocol (DWEHC) [15] is an extension to HEED. The main objective of DWEHC is to improve HEED by building balanced cluster sizes and optimize the intra-cluster topology using location awareness of the nodes. DWEHC makes no assumptions on the size and the density of the network. Moreover, each node implements DWEHC individually and the algorithm ends after some iterations that are executed by a distributed manner.

DWEHC builds a multi-level structure for intra-cluster communication and limits the number of parent nodes of children. Moreover, the only locally calculated parameter weight is defined for cluster head election. After locating the neighboring nodes, each node calculates its weight according to

$$W_{\text{weight}}(s) = \frac{E_{\text{residual}}(s)}{E_{\text{initial}}(s)} \times \sum_{u} \frac{R-d}{6R} \tag{3}$$

where $E_{\text{residual}}(s)$ and $E_{\text{initial}}(s)$ are respectively residual and initial energy at node s, R is the cluster range that corresponds to how far from the cluster head to a node inside a cluster, and d is the distance between node s and the neighboring node u. In a neighborhood, according to formula (3), the node with largest weight would be elected a cluster head and other nodes become members. At this stage, member nodes are considered as 1-level nodes and communicate directly with the cluster head. A member node can progressively adjust such membership in order to reach a cluster head using the least amount of energy. Given the node's knowledge of the distance to its neighbors, it can assess whether it is better to stay a 1-level member or become a h-level one where h is the number of hops from the cluster head to itself. If a member node can save energy while reaching its cluster head with more than one hop, it will become a h-level member. This process will continue until all nodes achieve the most energy-efficient intra-cluster topology. To limit the number of levels, every cluster is assigned a cluster range R within which member nodes should lay. The structure of multi-level cluster in DWEHC is illustrated in **Fig. 2**. After running DWEHC, a node either becomes a cluster head or becomes a child in a cluster.

Both DWEHC and HEED are similar in many ways. Due to energy reserve during the process of cluster head election, DWEHC generates more well-balanced cluster heads distribution and achieves significantly lower energy consumption in intra-cluster and inter-cluster routing than that in HEED. Moreover, the clustering process of DWEHC does not depend on any network topology or size. However, location knowledge required by DWEHC is not always easy to be available, because it needs specific hardware or equipment.

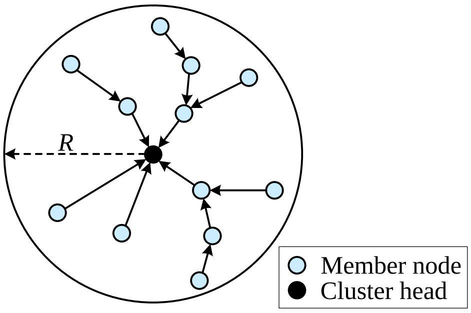

Fig. 2. The structure of multi-level cluster in DWEHC

4.1.4 UCS

Unequal Clustering Size (UCS) model [16] was proposed to balance energy consumption of cluster heads and prolong the network lifetime. In UCS, the sensing field is assumed to be circular and is divided into two concentric circles, called layers. The designers of this algorithm approximated the sensing field as pie shaped field with a multiple-layer network, shown in **Fig. 3**. It is assumed that all clusters in one layer have the same size and shape, but the sizes and shapes of clusters in the two layers are different. The position of a cluster head within the cluster boundaries determines the overall energy consumption of nodes that belong to the cluster. To keep the total energy consumption within the cluster as small as possible, every cluster head should be positioned at the center of the cluster. Cluster heads are deterministically deployed in the network and are assumed to be super nodes which possess much more energy than other nodes. By varying the radius of the first layer around the sink, while assuming a constant number of clusters in every layer, the area covered by clusters in each layer can be changed, accordingly the number of the nodes contained in a particular cluster can be changed. Data dissemination is performed through hop-by-hop, where every cluster head send its data to the closest cluster head in the direction of the base station.

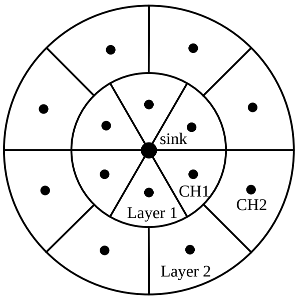

Fig. 3. Multiple-layer network topology in UCS

UCS can balance energy consumption among different cluster heads and prolong the network lifetime to some extent, since it builds clusters with different sizes and shapes and maintain relatively uniform communication load among all cluster heads. However, UCS is constrained by the assumption that the network is heterogeneous, and cluster heads have more energy and pre-determined locations. In other words, it lacks universality [32]. Additionally, cluster heads are required to locate in the center of the cluster regardless of residual energy, so it can not completely achieve energy-consumption balancing in UCS.

4.1.5 EECS

Energy Efficient Clustering Scheme (EECS) [17] is a clustering algorithm which better suits the periodical data gathering applications. In EECS, a network is grouped into several clusters and data transmission is performed by single-hop communication between the cluster head and the base station. Moreover, cluster head candidates compete for the ability to elevate to cluster head for a given round, and this competition is executed by candidates to broadcast their residual energy to their neighboring candidates. If a given node can not find a node with more residual energy, it becomes a cluster head. In addition, EECS extends LEACH by dynamic sizing of clusters based on cluster distance from the base station.

In EECS, a node selects the cluster head by considering both energy and load balancing among cluster heads, i.e. two distance factors: $d(P_j, CH_i)$ and $d(CH_i, BS)$. A weighted function $cost(j,i)$ is introduced for the ordinary node P_j to make a decision, which is

$$cost(j,i) = ((1 - w(P_j))w \times f(P_j, CH_i) + w(P_j) \times g(CH_i) \tag{4}$$

and node P_j selects cluster head CH_i with the minimal $\{cost\}$ to join. In formula (4), f and g are two normalized functions for the distance $d(P_j, CH_i)$ and $d(CH_i, BS)$. Function f in $cost$ guarantees that nodes select the closest cluster head in order to minimize the intra-cluster communication cost, while function g makes the nodes join the cluster head with small $d(CH_i, BS)$ to alleviate the workload of the cluster heads farther from the base station.

Considering energy and distance, EECS constructs balancing point between intra-cluster energy consumption and inter-cluster communication load. However, there exist a few problems to be considered in this algorithm. Firstly, account of single-hop communications in EECS, long-range transmissions directly from cluster heads to the base station can lead to much energy consumption. Hence it is not suitable to large-scope networks. Moreover, it requires more global knowledge about the distances between the cluster heads and the base station, and the task of global data aggregation adds overheads to all nodes. Finally, EECS needs much control overhead complexity because each node must compete for cluster-head election.

4.1.6 TEEN

Threshold sensitive Energy Efficient sensor Network protocol (TEEN) [18] is a clustering routing protocol and its main goal is to cope with sadden changes in time-critical applications. In TEEN, nodes sense their environment continuously, but energy consumption in this scheme can potentially be much less than that in proactive networks, because data transmission is done less frequently. In this protocol, a 2-tier clustering topology is constructed as illuminated in **Fig. 4** and two thresholds, hard threshold and soft threshold, are defined. The former threshold is a threshold value for the sensed attribute and 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. The latter threshold is a small change in the value of the sensed attribute which triggers the node to switch on its transmitter and transmit.

In TEEN, a cluster head sends its members a hard threshold and a soft threshold. Thus the hard threshold tries to reduce data communications by allowing the nodes to transmit only when the sensed attribute is in the range of interest. The soft threshold further reduces data communications might have otherwise occurred when there is little or no change in the sensed attribute. At the expense of increased energy consumption, a smaller value of the soft threshold generates more accurate information of the network, thus users can control the trade-off between energy efficiency and data accuracy by the method of parameters adjustment.

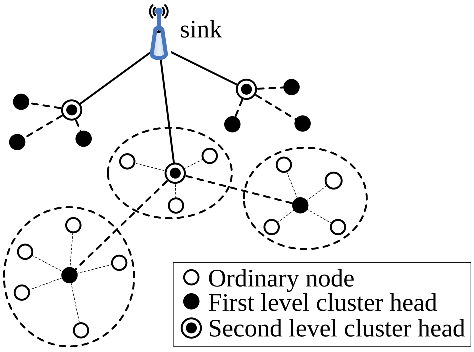

Fig. 4. The 2-tier clustering topology in TEEN

TEEN is suitable for time critical sensing applications and the energy consumption in this scheme is less than the proactive networks. Moreover, the soft threshold can be varied and the users can change the fresh parameters as required at every cluster change time. However, TEEN is not suitable for periodic reports applications since the user may not get any data at all if the values of the attributes may not reach the threshold [33]. Additionally, there exist a fact of wasted time-slots and a possibility that the sink may not be able to distinguish dead nodes from alive ones.

4.1.7 BCDCP

Base-station Controlled Dynamic Clustering Protocol (BCDCP) [19] is a centralized clustering routing protocol whose base station has the capability of complex computation. The main idea of BCDCP is the cluster formation where each cluster head serves an almost equal number of member nodes to balance overload among cluster heads and uniform cluster-head placement throughout the network.

At the beginning of cluster formation, the base station receives information on residual energy from all the nodes in the network. Based on this information, the base station computes the average energy level of all the nodes in the network, and then chooses a set of nodes whose energy levels are above the average value. Only the nodes from the chosen set can be elected cluster heads for the current round. Based on the set, the base station computes the number of clusters and performs the task of clustering, which is accomplished according to an iterative cluster splitting algorithm. This algorithm first splits the network into two sub-clusters, and proceeds further by splitting the sub-clusters into smaller clusters. This process will be repeated until the desired cluster number is achieved. At each iteration of cluster splitting, two nodes with the maximum separation distance are selected to be cluster heads from the chosen set where all the nodes are eligible to become cluster heads. Then, each remaining node in the current cluster is grouped with one cluster head or the other, whichever is closest. After balancing the two groups with approximately the same number of nodes, the two sub-clusters are formed.

In BCDCP, data transmission is performed by a multi-hop routing scheme. Once the clusters and the cluster heads have been identified, the base station chooses the lowest-energy path and transfer information to the nodes along with the details on cluster groupings and selected cluster heads. The routing paths are selected by first connecting all the cluster heads by means of the Minimum Spanning Tree (MST) approach [34], which minimizes the energy consumption for each cluster head, and then randomly choosing one cluster head node to forward the data to the base station. **Fig. 5** is the topology of the network in BCDCP.

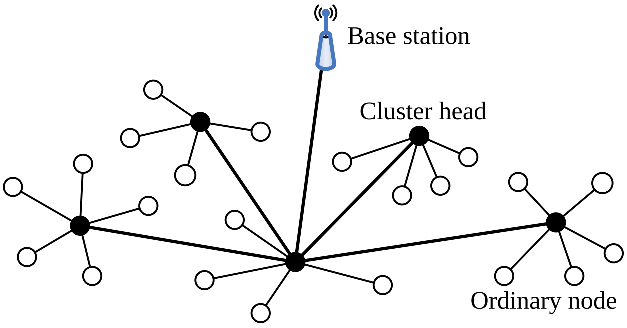

Fig. 5. The topology of the network in BCDCP

BCDCP utilizes a high-energy base station to set up clusters and uses MST [34] to connect cluster heads and randomly chooses a leader to send data to the base station. This algorithm resolves the problem of cluster head distribution and ensures similar power dissipation among cluster heads. However, there exist a few disadvantages in BCDCP. First, it is a centralized algorithm, which brings worse scalability and robust in large-scale networks compared with distributed algorithms. Secondly, due to single-hop intra-cluster communications, it is not appropriated for long-distance data transmission, which leads to much energy consumption. Thus, BCDCP is unfit for large-scope networks. Finally, BCDCP is not suitable for reactive networks where the user is not interested in periodic data retrieval.

4.2 Grid-based Clustering Routing Algorithms

4.2.1 GAF

Geographic Adaptive Fidelity (GAF) [20] is an energy-aware routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to WSNs as well. Strictly speaking, GAF is a location-based routing algorithm, but it may be considered as a clustering algorithm where the clusters are based on geographic location.

The network area is divided into fixed virtual grids, namely clusters, in GAF. The virtual grids are small enough that each node in a cell can directly communicate with each node from an adjacent cell. Inside each grid, nodes collaborate with each other and play different roles. For example, one sensor node will be elected to stay awake for a certain period of time, and then the rest go to sleep. The awake node is responsible for monitoring and reporting data to the base station on behalf of all the nodes in the zone. According to GPS location, each node associates itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. For saving energy, such equivalence is exploited in keeping some nodes located in sleeping state. Thus, GAF can greatly prolong the network lifetime as the number of nodes increases. As an example, the virtual grid is divided into two adjacent zones in **Fig. 6**. In this figure, nodes C_3, C_4 and C_5 are equivalent and any two of them can sleep. There are three states defined in GAF: (i) discovery, for determining the neighbors in the grid, (ii) active, reflecting participation in routing and (iii) sleep, when the radio is turned off. In order to handle the mobility, each node in the grid estimates its leaving time of the grid and sends it to its neighbors. The sleeping neighbors adjust their sleeping time accordingly in order to keep routing fidelity. Before the leaving time of the active node expires, sleeping nodes wake up and one of them becomes active, i.e. serves as a cluster head.

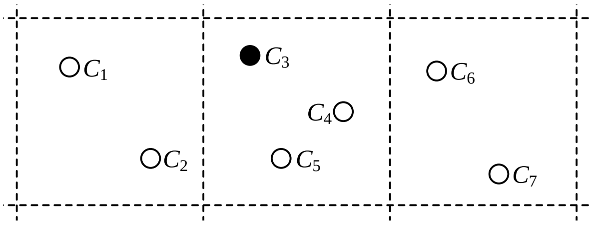

Fig. 6. The virtual grids in GAF

In GAF, nodes belonging to the same cell coordinate active and sleep periods and at least one node is active in a cell. Hence, the routing fidelity is maintained. Furthermore, GAF can increase the lifetime of the network by saving energy. However, GAF may results in large traffic injection, and the delay is not predictable and bounded. This makes it unsuitable for real-time scenarios in WSNs.

4.2.2 PANEL

Position-based Aggregator Node Election protocol (PANEL) [21] is a position-based clustering routing algorithm for WSN. This algorithm supports asynchronous sensor network applications where the sensor node readings are fetched by the base stations. The main goal of PANEL is to elect cluster heads for reliable and persistent data storage applications.

PANEL assumes that nodes are deployed in a bounded area, which is partitioned into geographical clusters and introduces a notion of reference point. At the beginning of each epoch, a reference point R_j is computed in each cluster j by the nodes in a distributed manner in terms of the epoch number, as follows

$$\vec{R}_j = \vec{Q}_j + \vec{Q} \tag{5}$$

where $\vec{Q}_j$ is the position of the lower-left corner of cluster j. Furthermore, the current epoch number e is known by every node and the computation consists in calling a pseudo-random function $H(e)$ that maps e to a relative position $\vec{Q}$ inside the cluster. Once the reference point is computed, the node that is the closest to the reference point will be elected the cluster head for the given epoch. The reference points of the clusters will be re-computed and the cluster head election procedure will be re-executed in next epochs. This cluster head election procedure ensures load balancing in PANEL because each node of the cluster can become cluster head with almost the same probability. The illustration of the geographical clustering in PANEL is shown in **Fig. 7**. The cluster head election procedure needs intra-cluster communications. PANEL takes advantage of these communications to establish routing tables for intra-cluster routing. Especially, at the end of the cluster head election procedure, the nodes also are conscious of the next hop towards the cluster head elected for the current epoch. Moreover, a position-based routing protocol is introduced for inter-cluster communications in PANEL.

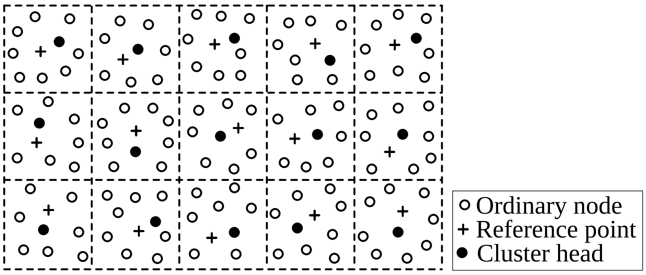

Fig. 7. The geographical clustering in PANEL

PANEL can be integrated with position-based routing protocol for inter-cluster communications. The procedure of cluster head election in PANEL ensures load balancing, and can prolong network lifetime due to reduction of communication load thanks to data aggregation. However, the main disadvantage of PANEL is the assumption that clusters are determined before deployment, thus this algorithm can not be well applied in WSN dynamics.

4.2.3 TTDD

The Two-Tier Data Dissemination (TTDD) [22] is a grid-based clustering algorithm, which provides data delivery to multiple mobile sinks in WSNs.

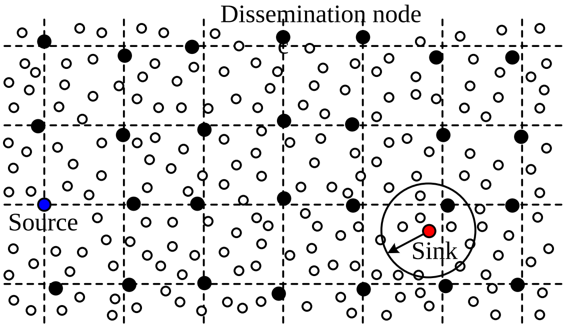

Fig. 8. The grid-based topology in TTDD

In TTDD, a source divides the field into a grid of square cell. A source, at one crossing point of the grid, propagates data announcements to reach all the other crossings, called dissemination points, on the grid as shown in **Fig. 8**. In TTDD, a source calculates the locations of its four neighboring dissemination points and sends a data announcement message to the four neighboring dissemination points using simple greedy geographical forwarding. Similarly, the neighbor node continues relaying the data announcement message till the message stops at a node that is closer to the dissemination point than all its neighbors. During this process, each intermediate node stores the source information and this process continues until the message stops at the border of the network. The sink can flood a query within a local area. Once the query reaches a local dissemination node, it is forwarded on the grid to the upstream dissemination node. The query is forwarded by the upstream toward the source, until finally arrives at the source. During the above process, each dissemination node stores the location of the downstream dissemination node, thus this information is used to direct data back to the sink. When a sink moves, trajectory forwarding is performed to send data to the mobile sink from its immediate dissemination node. In trajectory forwarding, each sink is associated with two nodes: a primary agent and an immediate agent. A sink picks a neighboring node as its primary agent which receives data directly from the immediate dissemination node, and subsequently sends data to the sink. Initially, the primary agent and the immediate agent are the same node. When a sink is about to move out of the range of its immediate agent, it selects another neighboring node as its new immediate agent and sends the information of the new immediate agent to its primary agent, thus future data is delivered to the new immediate agent.

TTDD can provide scalable and efficient data delivery from multiple sources to multiple and mobile sinks, but there are some problems to be considered. Firstly, the routing of a forwarding path in TTDD is not the shortest path, thus it may lead to large latency, especially, on a long path. Furthermore, the grid structure formation and query flooding cost large energy consumption. Finally, if mobile sensor nodes are allowed to move in the network, it is hard for TTDD to cope with it.

4.2.4 HGMR

Hierarchical Geographic Multicast Routing (HGMR) [23] is a location-based multicast algorithm. This algorithm seamlessly incorporates the concepts of Geographic Multicast Routing (GMR) [35] and Hierarchical Rendezvous Point Multicast (HRPM) algorithms [36], and optimizes them by providing forwarding energy efficiency as well as scalability to large-scale WSNs.

HGMR starts with a hierarchical decomposition of a multicast group into subgroup of manageable size by means of the concept of mobile geographic hashing of HRPM. Within each subgroup, HGMR adopts the local multicast scheme of GMR to relay data packets along multiple branches of the multicast tree in one transmission. In HGMR, the multicast group is divided into subgroups using the mobile geographic hashing idea: the deployment area is recursively partitioned into a number of d^2 equal-sized square sub-domains called cells, where d is decomposition index depending on the encoding overhead constraints, and each cell comprises a manageably-sized subgroup of members. In each cell, there is an Access Point (AP) responsible for all members in that cell, and all APs are managed by a Rendezvous Point (RP). A node generates the hashed location for the RP and sends a join message to that location. After receiving the value of decomposition index d from the RP, the node invokes the hash function with d and its location, to achieve the hashed location of the AP of the cell it belongs to. Consequently, the source builds an overlay tree, the Source → APs tree, whose vertices are active APs in a topology graph, and another overlay tree, the AP → Members tree is also built from the AP, considering each member as the vertex. When a source needs to transmit data packets, it utilizes the unicast-based forwarding strategy of HRPM to propagate data packets to each AP along the Source → APs overlay tree. In each cell, instead of building an AP → Members overlay tree, HGMR uses the cost over progress optimizing broadcast algorithm of GMR to select the next relay nodes at each hop.

In HGMR, the membership management is very simple without additional cost due to the geographic hashing algorithm. According to the number of the nodes which play different roles, the data transmission methods for different hierarchies in HGMR make the routing energy-efficient in a way. However, there are a few drawbacks in HGMR. First, the network is simply divided into a set of cells, thus it may lead to sub-optimal routing paths from the root node to multicast group members. Second, all transmissions are concentrated to APs, which can be changed to another node by hash function, but it is too limited in a cell, and may bring on unbalanced energy consumption around APs. Finally, HGMR makes the routing paths inefficient to some extent, in that data packets are forwarded from the upper APs to the lower APs hierarchically, whether the lower APs are closer to the source than the upper APs or not [37].

4.3 Chain-based Clustering Routing Algorithms

4.3.1 PEGASIS

Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [24], proposed by Lindsey S., et al., is an improvement of LEACH. The main idea of PEGASIS is for each node to only communicate with their close neighbors and take turns to be a leader for data transmission. This approach will evenly distribute communication load among all nodes in the network. In PEGASIS, all nodes are organized to form a chain, which is either constructed by the sink using a centralized assignment mode or built by the nodes themselves using a greedy algorithm. If a chain is formed by the nodes themselves, they can first get the location data of all nodes and locally compute the chain using the same greedy algorithm. During the process of chain formation in PEGASIS, it is assumed that all nodes have global knowledge of the network and the greedy algorithm is employed. Chain construction is commenced from the furthest node to the sink, and the closest neighbor to a node will be the next node on the chain. When a node on the chain dies, the chain will be reconstructed in the same way to bypass the dead node.

For gathering data in each round, each node receives data from one neighbor, fuses the data with its own, and transmits to the other neighbor on the chain. By moving from node to node, the fused data are eventually sent to the sink by the leader at a random position on the chain. The leader is important for nodes to die at random locations, in respect that the idea of nodes dying at random places is to enhance the robustness of the network. Alternatively, in each round, a control token passing approach initiated by the leader is used to start the data transmission from the ends of the chain. The scheme of data transmission in PEGASIS is shown in **Fig. 9**. In this figure, if node C_2 is the leader, it will pass the token along the chain to node C_0 at first. Then, node C_0 will pass its data toward node C_2. After node C_2 receives data from node C_1, it will pass the token to node C_4, and node C_4 will pass its data towards node C_2 with data fusion taking place along the chain.

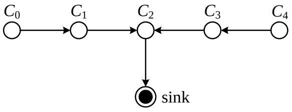

Fig. 9. The token passing scheme in PEGASIS

PEGASIS is able to outperform LEACH for different network sizes and topologies, in that it decreases the overhead of dynamic cluster formation in LEACH, and decrease the amount of transmitted data by data aggregation. However, there are some disadvantages in PEGASIAS. Firstly, the main disadvantage of PEGASIS is the necessity of having a complete view of the network topology at each node for chain construction and that all nodes must be able to transmit directly to the sink. Thus, this scheme is unsuitable for those networks with a time varying topology [38]. Secondly, it is assumed that each sensor node can be able to communicate with the sink directly, but nodes usually use multi-hop communications with the sink in practical cases. Thirdly, it is difficult for all nodes to maintain a complete database about the location of all other nodes in the network. In other words, this algorithm is lacking in scalability. Finally, on account of communicating with the sink directly, some single leaders can become a bottleneck.

4.3.2 CCS

Concentric Clustering Scheme (CCS) [25] has been proposed to reduce energy-consumption loopholes in PEGASIS. The main idea of CCS is to consider the location of the base station to enhance its performance and to prolong the lifetime of the network.

In CCS, the network is divided into some concentric circular tracks which represent different clusters, and each circular track is assigned with a level. The track nearest to the base station is assigned level-1 and the level number increases as it increases the distance from the base station, accordingly each node in the network is assigned its own level. Chains are constructed within the track, as that in PEGASIS. One of the nodes on the chain at each level area is selected as a cluster head. A cluster head in level L is selected with node number obtained by calculating $i \bmod M_L$, where M_L represents the number of nodes that have the same level in i round. Data transmission in CCS is based on the process of PEGASIS protocol. After cluster head selection, each cluster head transmits the data of its own location to both the upper and lower level cluster head in one grade. In this process, all nodes in each level transmit data to the nearest node from themselves along the chain. If a node receives data, it fuses its own data and transmits these data to the next node. Therefore, a cluster head receives at most two data messages. Subsequently, the cluster head in each level transmits the data to the lower cluster head. At last, the cluster head of level 1 transmits these data to the base station. The data transmission scheme in CCS is shown in **Fig. 10**.

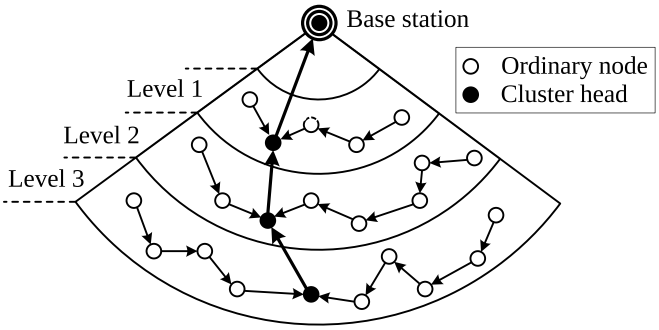

Fig. 10. The data transmission scheme in CCS

Compared with PEGASIS, the distance over which the data can be transmitted to the base station from the cluster head is reduced in CCS. Hence, a considerable amount of energy is saved on account of the reduction of transmission distance in CCS [39]. However, there are some problems to be considered. Firstly, node distribution in each level is unbalanced, thus the levels with small number of nodes will deplete their energy first, in that these nodes have high probability of being elected to cluster heads. Secondly, chain-based algorithms enable nodes to communicate with their closest neighbor by using low radio power, but the long chain would cause large delay [40]. Finally, routing is based on the location rather than the residual energy of nodes, thus energy of cluster heads may dissipates quickly on the path among cluster heads, and even energy holes will appear in the network.

4.3.3 TSC

Track-Sector Clustering (TSC) [26] is basically a clustering algorithm with one cluster head selected in each cluster. In TSC, the network is divided into concentric circular tracks and triangular sectors. By minimizing redundant data transmission and providing shortest distance between cluster heads and the base station, the division of tracks and sectors saves energy cost.

The topology of TSC is depicted in **Fig. 11**. Using tracks and sectors to form clusters in TSC, a cluster is an area under curved strip formed by the intersection of a circular track and a triangular sector. Different form PEGISIS, TSC reduces redundant data transmission by tracks and sectors which break the long chain in the track into smaller chains in the network. Besides, it reduces the total distance for data transmission from nodes to the respective cluster heads and finally to the base station. Furthermore, the amount of data gathered in the cluster head in TSC is still not greater than that in CCS.

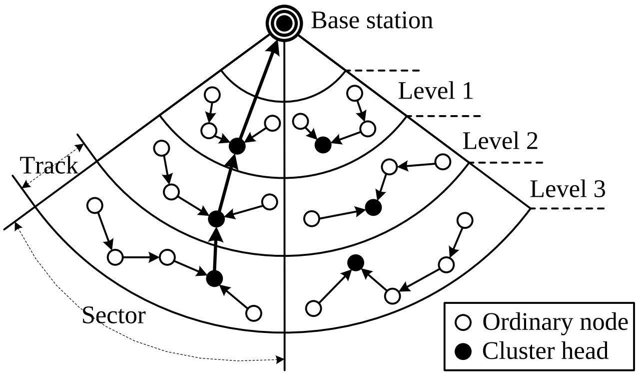

Fig. 11. The data transmission scheme in TSC

The executing process of TSC is divided into four phases: track setup, sector setup and cluster-head selection, chain construction, and data transmission. For track setup, the base station sets the concentric circular tracks with itself as the geometric center of the concentric circular tracks. Each node is assigned the respective track by the signal strength and the position information of itself. Each track is assigned a level. The total number of tracks depends on the parameters such as node density and the location of the base station. For sector setup and cluster-head selection, sectors are constructed and a few cluster heads are selected by the base station. The number of cluster heads is equal to the number of sectors. Firstly, a cluster head is selected at random in level-1 track. Based on the position of the selected cluster head, the transmission slope of the selected head node with respect to the base station is calculated by the base station. Then, the node that has transmission slope similar to that at level-1 track is selected in each of the higher level tracks. For chain construction, chains are constructed within each cluster area formed by the intersection of tracks and sectors. The cluster heads are selected as described in sector setup and head node selection phase, then the cluster heads in the chain are selected with the node number obtained by calculating the value of mod. For data transmission, all the member nodes in a cluster receive and transmit data to the neighbor node in their respective clusters. The cluster head in each cluster aggregates the data and transmits to the cluster head of the cluster in lower level track. Finally, the data is transmitted to the base station by multiple hops.

Compared with PEGASIS and CCS, TSC with tracks and sectors reduces redundant data transmission in the network by breaking the long chain into smaller chains. Also, it reduces the total distance for data transmission from the nodes to their respective cluster heads and finally to the base station. In a word, this scheme is more energy efficient as compared to PEGASIS and CCS. However, there are some problems to be considered. Firstly, similar to that in CCS, the node distribution in each level is unbalanced in TSC, thus the levels with small number of nodes will deplete their energy first. Moreover, residual energy is not considered for cluster head election, so this scheme may lead to unbalanced energy consumption across the network.

5. Comparison of Typical Clustering Routing Algorithms in WSNs

The above mentioned cluster routing algorithms in WSNs are different in a variety of aspects. At this point, we compare the different clustering routing approaches, which are shown in **Table 1**. As seen in this table, some conclusions will be summarized as follows.

One of the most principal considerations in WSNs is energy efficiency that allows longer network lifetime. According to the current typical clustering routing protocols in WSNs, energy efficiency must be further increased. It is indispensable to save energy cost for intra-cluster and inter-cluster communications all the more.

Load balancing is required for clustering routing design. Based on keeping network coverage and connectivity, clustering methods should guarantee low overhead as well as optimal traffic distribution among all cluster heads.

Centralized clustering algorithms need too much communication load, which results in relatively low energy efficiency in WSNs. In other words, centralized clustering algorithms are not scalable and not suitable for large-scale networks.

Single-hop communication, between cluster heads and the base station, needs much energy cost and does fit large-scale networks. Namely, the algorithms with single-hop communications are lacking in scalability.

6. Conclusions

WSNs have aroused much interest over the past few years and significant attention has been paid to clustering routing algorithms. In this paper, we have presented a comprehensive overview of clustering routing algorithms in WSNs. We have discussed the advantages and classification of clustering routing algorithms in WSNs. In particular, we have systematically analyzed the typical clustering routing algorithms in WSNs. In addition, we have compared and contrasted different approaches on the basis of various performance measures.

It is clear that these different clustering routing algorithms mentioned above are encouraging for improving the performances of WSNs. However, some issues remain to be considered and there are still some open questions. First of all, it remains a challenging problem how cluster formation is performed in heterogeneous WSNs where different types of sensor nodes are deployed and each of them has different communication and processing capabilities. Moreover, in a large-scale WSN with both location-aware and location-unaware sensor nodes, scalable and distributed adaptive clustering routing approaches with flexible number of iterations are especially expected. Finally, with the increase of functionality requirements of sensor nodes, it is challenging to increase both energy efficiency and scalability of the network.

Table 1. Comparison of Typical Clustering Routing Algorithms in WSNs

Algorithm Type	Algorithm Name	Network Type	Cluster-Formation Mode	Position Awareness	Mobility	Intra-cluster Topology	Inter-cluster Topology	Energy Efficiency	Scalability	Delivery Delay	Load Balancing	Algorithm Complexity
block-based clustering routing algorithms	LEACH	proactive	distributed	no	no	one-hop	one-hop	low	low	low	medium	low
	HEED	proactive	distributed	no	no	one-hop	one-hop multi-hop	medium	medium	medium	medium	medium
	DWEHC	proactive	distributed	yes	no	multi-hop	multi-hop	high	medium	medium	good	medium
	UCS	proactive	distributed	no	no	one-hop	multi-hop	low	low	low	low	medium
	EECS	proactive	distributed	no	no	one-hop	one-hop	medium	low	low	medium	high
	TEEN	reactive	distributed	no	no	one-hop two-hop	one-hop	high	low	low	good	high
	BCDCP	proactive	centralized	no	no	one-hop	one-hop	low	low	low	good	high
grid-based clustering routing algorithms	GAF	proactive	distributed	yes	no	One-hop	multi-hop	medium	high	low	medium	medium
	PANEL	proactive	distributed	yes	no	multi-hop	multi-hop	medium	low	medium	good	high
	TTDD	proactive	distributed	yes	yes	multi-hop	multi-hop	low	low	high	good	low
	HGMR	proactive	distributed	yes	no	multi-hop	multi-hop	medium	high	medium	low	medium
chain-based clustering routing algorithms	PEGASIS	proactive	distributed	no	no	multi-hop	one-hop	low	low	high	medium	high
	CCS	proactive	distributed	no	no	multi-hop	multi-hop	low	medium	medium	low	medium
	TSC	proactive	distributed	no	no	multi-hop	multi-hop	medium	medium	medium	low	medium

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