

Atypical Hierarchical Routing Protocols for Wireless Sensor Networks: A Review

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Abstract—Hierarchical routing in wireless sensor networks (WSNs) is a very important topic that has been attracting the research community in the last decade. Typical hierarchical routing is called clustering routing in which the network is divided into multiple clusters. Recently some types of atypical hierarchical routing arise, including chain-based, tree-based, grid-based routing, and area-based routing. There are several survey papers that present and compare the hierarchical routing protocols from various perspectives, but a survey on atypical hierarchical routing is still missing. This paper makes a first attempt to provide a comprehensive review on atypical hierarchical routing. We offer a classification of atypical hierarchical routing of WSNs, and give detailed analysis of different logical topologies. The most representative atypical hierarchical routing protocols are described, discussed, and qualitatively compared. In particular, the advantages and disadvantages of different atypical hierarchical routing protocols are analyzed with respect to their significant performances and application scenarios. Finally, we put forward some open issues concerning the design of hierarchical WSNs. This survey aims to provide useful guidance for system designers on how to evaluate and select appropriate logical topologies and hierarchical routing protocols for specific applications.

Index Terms—Wireless sensor networks, atypical hierarchical routing, chain-based, tree-based, grid-based, area-based

I. INTRODUCTION

WIRELESS sensor networks (WSNs) consist of a large number of low-cost, low-power and intelligent sensor nodes and one or more sinks or base stations (BSs) [1], [2]. Those nodes are small in size and can perform many important functions, including event sensing, information processing, and data communication [3], [4]. WSNs can be employed in wide military applications and civilian scenarios [5], [6]. Due to various advantages such as ease of deployment, extended transmission range, and self-organization, WSNs have been replacing the traditional networks.

Sensors are generally equipped with non-rechargeable batteries, so energy efficiency is a major design issue in order to increase the network lifespan [7]. Data transmission is the major source of energy consumption [8], and it is a serious challenge to design an energy efficient routing scheme for prolonging the network lifetime [9], [10]. Furthermore, as the network scale increases, the scalability of the network becomes a very important issue. Hierarchical architecture is proved to be

an effective solution to the problem of scalability and energy efficiency. In a hierarchical architecture, the network is divided into different layers, and nodes in different layers perform different tasks. The typical hierarchical routing technique is clustering, in which the network is partitioned into multiple clusters and nodes undertake two different tasks, cluster heads (CHs) and ordinary nodes (ONs). An ON only delivers its sensed data to its related CH, while a CH is responsible for collecting the data from its ONs and transferring data to the sink via hierarchical routing. LEACH [11] is a pioneering cluster routing protocol for WSNs, and various sequent protocols have been proposed to form the so-called LEACH family, such as [12]-[20].

Recently there arise some atypical hierarchical routings, which are variants of cluster-base routing and present special hierarchical architecture, including chain-based, tree-based, grid-based, and area-based routing. These types of atypical hierarchical routing are similar to the traditional clustering routing, but are more or less different in hierarchy division and communication scheme. There exist several survey papers that present and compare the hierarchical routing protocols of WSNs from various perspectives, but so far no work focuses on atypical hierarchical routing. Motivated by this, we make a first attempt to provide a comprehensive survey on atypical hierarchical routing for WSNs.

The main contributions of our work can be summarized as follows.

- 1) We offer a classification method with respect to atypical hierarchical routing for WSNs. This provides a new perspective for readers to understand this kind of routing. As far as we know, it is the first time for atypical hierarchical routing to be sorted into four categories based on logical topologies.
- 2) We give a detailed analysis of different logical topologies for atypical hierarchical routing with their advantages and disadvantages. To the best of our knowledge, this is the most comprehensive review of logical topologies for typical hierarchical routing of WSNs.
- 3) It is a first attempt to present a comprehensive review of atypical hierarchical routing protocols of WSNs. This review consists of several traditional and up-to-date atypical hierarchical routing protocols with their characteristics, strengths, as well as weaknesses.
- 4) We provide a comprehensive comparison of different atypical hierarchical routing protocols concerning their general performances and application scenarios. This may help network designers to select suitable hierarchical routing protocols for specific applications.
- 5) A few open issues for this research domain are summarized. New research directions for researchers are pointed out, which contribute to further development of this research area.

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The remainder of this paper is organized as follows: Section II provides an overview of surveying typical hierarchical routing protocols for WSNs. Section III makes a detailed analysis of different topologies for atypical hierarchical routing of WSNs. Section IV provides a comprehensive review on some representative atypical hierarchical routing protocols with respect to their characteristics, strengths and drawbacks. Different atypical hierarchical routing protocols with respect to their performances and application scenarios are compared in Section V. Some open issues are discussed in Section VI. Finally, this paper is concluded in Section VII.

II. RELATED WORK

In this section, we summarize the previous surveys of typical hierarchical algorithms for WSNs in the literature.

At early times, Arboleda et al. [21] specialized hierarchical routing protocols and presented a comparison survey between different clustering protocols for WSNs. Abbasi et al. [22] presented an influential survey on clustering algorithms for WSNs. This survey proposed a detailed taxonomy and classification of typical clustering schemes. Kumarawadu et al. [23] also surveyed the clustering protocols for WSNs and presented a classification of clustering protocols on the basis of the cluster formation parameters and CH election criteria, and described the popular clustering protocols. Deosarkar et al. [24] studied clustering schemes and summarized some limitations of a representative hierarchical routing protocol. Several aspects and characteristics of typical clustering algorithms in WSNs are discussed in [25] regarding clustering timings, attributes, metrics, advantages and disadvantages. By considering energy efficiency, Maimour et al. [26] presented a review on clustering algorithms for WSNs from the perspective of data routing. Some important clustering algorithms were reviewed in [27], in which a few metrics, such as residual energy, and uniformity of CH distribution were analyzed. In [28], the famous clustering algorithm LEACH [11] and its descendant were discussed regarding the advantages and disadvantages. Naeimi et al. [29] presented a survey on the taxonomy of the clustering routing protocols according to their objectives and methods towards addressing the shortcomings of clustering process. In [30], the advantages and objectives of clustering for WSNs were outlined, and a comprehensive taxonomy of clustering methods for WSNs were presented. In particular, some prominent clustering routing protocols for WSNs were described and analyzed according to the protocol implementation stages. The authors in [31] analyzed many challenging factors that influenced design of routing protocols in WSNs, and discussed many efficient clustering based routing protocols. Tyagi and Kumar [32] provided a detailed taxonomy of various clustering and routing techniques in WSNs based upon general metrics, including power management, energy management, network lifetime, etc. The successful application of fuzzy logic in WSNs is illustrated in [33], in which clustering protocols based on fuzzy logic are simply surveyed regarding CH election. A concise survey on neural network based clustering approaches is presented in [34]. A taxonomy of clustering algorithms and a categorizing framework are proposed in [35] which covers major factors in the selection of a suitable algorithm for big

data. A comprehensive survey on clustering approaches are provided based on equality of cluster size in [36], which provides a classification of clustering algorithms of WSNs.

Here we summarize the previous related work in Table I, which highlights the classification method of typical hierarchical routing protocols along with the year of the survey.

TABLE I
SURVEYS ON ATYPICAL HIERARCHICAL ROUTING PROTOCOLS IN WSNs

Publication year	Author(s)	Literature	Classification criteria for routing survey
2006	Arboleda <i>et al.</i>	[21]	Proactivity
2007	Abbasi <i>et al.</i>	[22]	Convergence time
2008	Kumarawadu <i>et al.</i>	[23]	Clustering parameters CH election criteria
2008	Deosarkar <i>et al.</i>	[24]	CH election criteria
2009	Jiang <i>et al.</i>	[25]	No
2010	Maimour <i>et al.</i>	[26]	Proactivity
2010	Boyinbode <i>et al.</i>	[27]	No
2011	Kumar <i>et al.</i>	[28]	No
2012	Naeimi <i>et al.</i>	[29]	Whole clustering process
2012	Liu	[30]	Implementation stage
2012	Haneef <i>et al.</i>	[31]	No
2013	Tyagi <i>et al.</i>	[32]	General metrics
2013	Kumari <i>et al.</i>	[33]	No
2013	Subhai <i>et al.</i>	[34]	No
2014	Fahad <i>et al.</i>	[35]	No
2014	Afsar <i>et al.</i>	[36]	equality of cluster size

III. ANALYSIS OF LOGICAL TOPOLOGIES FOR ATYPICAL HIERARCHICAL ROUTING

In this section, we analyze the classification of atypical hierarchical routing of WSNs and their characteristics.

A. Classification of Atypical Hierarchical Routing Protocols

We present a classification for atypical hierarchical routing, which is divided into four categories, chain-based, tree-based, grid-based, and area-based according to topologies. Fig. 1 and Fig. 2 respectively show the classification and the different types of atypical hierarchical routing in WSNs.

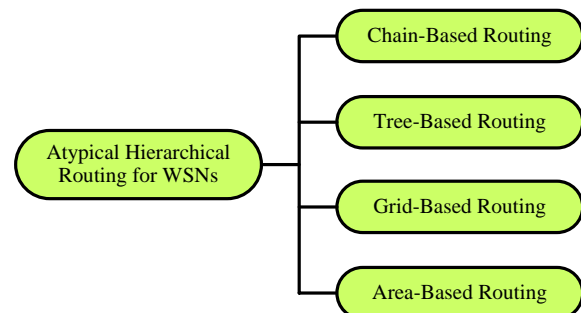


Fig. 1. Classification of hierarchical routing for WSNs

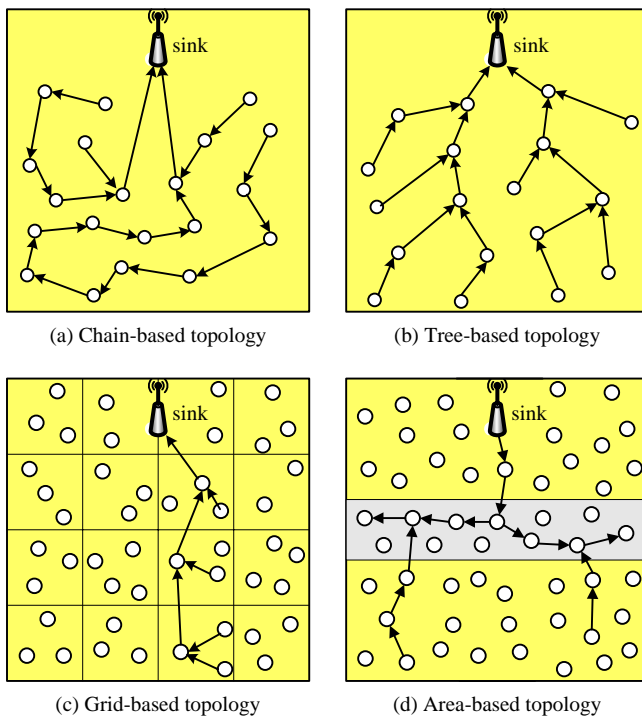


Fig. 2. Different topologies of atypical hierarchical routing for WSNs

B. Chain-Based Routing

1) Basic Description

In chain-based topology, one or more chains are constructed to connect the deployed sensor nodes for data transmission. In a chain, a leader is selected to perform the task of data collecting, like a sink. Data is delivered along the chain, and ultimately to the leader node. Data aggregation is performed during the process of transmission.

2) Advantages

Simple topology: For chain-based routing, it has a simple topology compared with traditional cluster-based routing, because such a topology is easy to implement and maintain. For example, chain-based routing needn't CH competition and OH selection.

Energy saving of local communication: In chain-based routing, a node only sends data to its next node, which is very close to it. So, a part of energy is saved by local communication compared with intra-cluster communication in cluster-based topology.

3) Disadvantages

Large delay: The whole network is organized to one or multiple chains in chain-based topology, and generally a chain is very long with large number of hops from one end to the other in the chain. Thus, data transmission needs large delay by large number of hops.

Imbalance of energy consumption: In such a topology, hop-by-hop data transmission is performed, so nodes far from the leader nodes have little data to deliver, while the nodes near the leader node suffer from too much data traffic. Thus, energy consumption is not balanced in such a topology.

Less robustness: It is not resilient to node failures in chain-based topology. If a sensor node fails, data transmission

have to be terminated from the end of the chain to the failed node. Thus, chain-based topology has less ability of robustness.

C. Tree-Based Routing

1) Basic Description

In tree-based routing, a logical tree is constructed by all sensor nodes. Data is delivered from leaf nodes to their parent ones severally. In turn, the parent nodes send the received data to their parent nodes towards to root nodes. Data aggregation is possibly performed in each node.

2) Advantages

Simple topology structure: Similar to chain-based topology, tree-topology is simpler than cluster-based routing which includes a relatively complex process of cluster formation. Likewise, CH competition and OH selection don't exist in such a topology.

Less energy consumption: Energy consumption is decreased compared with that in flat routing in WSNs, because flooding is not necessary for data transmission. Similar to chain-based routing, data transmission is performed between neighbor nodes. This can save much energy consumption.

3) Disadvantages

Less robustness: Similar to chain-based topology, it is not resilient to node failures in tree-based topology. If a sensor node fails, the relative whole sub-tree is unable to work and new tree construction is needed.

Uneven energy consumption: In tree-based topology, power consumption is uneven across the network. This is similar to chain-based topology, the nodes closer to the BS perform more load in forwarding packets.

Less scalability: In large-scale tree-based networks, too many levels are constructed from one root to relative leaves. Thus, it will result in large latency and energy consumption for data transmission.

D. Grid-Based Routing

1) Basic Description

In a grid-based topology, the network is divided into various grids by geography approach. Thus, grid-based routing generally belongs to location-aware routing. The distinct characteristic of the type of routing is that the routing operation is performed without any routing table. Once the position of the destination is achieved by the source, all routing operations are locally performed.

2) Advantages

Simple structure: In grid-based networks, grids are regularly constructed by geographic locations, and CH competition and ON selection can be left out. So the hierarchical structure is simple compared with cluster-based routing.

Efficient data delivery: It can provide efficient data delivery in WSNs, in that each node only maintains a simple forwarder candidate set for it to transmit data. This is different from traditional cluster-based topology, in which many more delay candidates can be selected.

3) Disadvantages

Limited load balancing: In grid-based networks, data transmission is performed along the grids, and energy efficiency depends on balancing the geographic distribution versus occurrence of traffic.

Overload: Data communication is performed along the grids, and generally the transmission routing is fixed. Thus any dependence of performance with traffic load thwarting the negligence of distance may occur in overload.

E. Area-Based Routing

1) Basic Description

Area-based topology is an up-to-date structure, in which some sensor nodes are designated in a specific area and act as high-tier nodes. Generally, such nodes perform the task of data collection from ONs and data transmission to the sink. The size of the area can be adjusted according to the load balancing requirements. Such topology is always used in mobile WSNs.

2) Advantages

Simple topology structure: Only a specific area must be determined and it is easy to determine which nodes act as high-tier tasks. Therefore, the structure of area-topology is also simpler than that of cluster-based routing which includes a relatively complex process of cluster establishment.

Less energy consumption: Energy consumption is decreased compared with that in some clustering routing in WSNs, because data exchange is performed in local regions. This can avoid long-distance communication and decrease large energy dissipation.

Good load balancing: In such as topology, generally a mobile sink moves. This prevents traffic load from being distributed in a small space. Therefore, it facilitates load balancing in the network.

3) Disadvantages

Less scalability: In a large-region network, a large area of specific region is needed. Data dissemination around the specific region results in large latency and energy consumption for data transmission.

High capital cost: Such a topology is generally used in mobile networks which contain high technology and difficult manufacturing. This can result in larger cost of network construction compared with that in static WSNs.

IV. REVIEW ON ATYPICAL HIERARCHICAL ROUTING PROTOCOLS IN WSNs

In this section, we select and analyze a few atypical hierarchical routing protocols of WSNs based on different logical topologies.

A. Chain-Based Hierarchical Routing Protocols

1) PEGASIS

PEGASIS (power-efficient gathering in sensor information systems) [37] is a pioneering chain-based hierarchical protocol. In PEGASIS, all nodes are organized into a linear chain for data transmission and data aggregation. The chain can be formed by the sink with a centralized approach or by a greedy algorithm with a distributed manner. It is assumed in both cases that all nodes have global knowledge of the network topology. If the

calculation task of the chain is assigned to nodes, they can first achieve the location information of all nodes and compute the chain using such a greedy manner. The chain construction is begun with the furthest node from the sink. The closest neighbor node is selected as the next node of the chain. If a node dies, the chain will be rebuilt using the same method to remove the dead node. Data is delivered from each node to its neighbor node, and nodes act as leaders which communicate to the sink in alteration. Every node fuses its neighbor's data with its own to generate a new packet and then delivers it to its next neighbor. This is a repeated course until all data are gathered at the leader, which then directly transmits the final data packet to the sink.

Compared with LEACH [11], PEGASIS reduces the overhead of clustering process and decreases the chance of data aggregation. To achieve load balancing, all sensor nodes act as the leader in turn [38]. However, it is difficult for all nodes to achieve global knowledge of node positions to select closest neighbors and minimize energy depletion. Moreover, as leaders, all nodes must be able to directly communicate with the sink. So, PEGASIS is not suitable for such networks with time varying topology [39]. In addition, the long chain structure suffers from large transmission delay. The increase of the network scale will make the above problems be worse. In other words, PEGASIS suffers from the problem of scalability.

2) CCS

CCS (concentric clustering scheme) [40] is centralized chain-based routing algorithm in which there exist multiple chains. The goal of CCS is to improve the energy efficiency of PEGASIS. The location of the BS is considered to achieve such a goal. The whole network is divided into several concentric circular tracks which represent different clusters with different levels. Level-1 is assigned to the track that is nearest to the BS. The larger the distance to the BS is, the larger the level number is. Multiple chains are created within the track. At each hierarchy, one node of the chain is elected as a CH. All nodes in each level transmit the data to the nearest node from themselves along the chain. After CH selection, data is delivered from one CH to its two one-hop neighbor CHs with different levels.

In CCS, Owing to relay communication from CH to CH, the distance between the CH to the BS is greatly reduced. Clearly, much energy consumption of data transmission is saved [41]. Due to the track structure, data transmission is within tracks and between tracks. So, data transmission that diverges from the BS is reduced. However, energy dissipation is not balanced because data is delivered in a relay style and the tracks closer to the BS have more data to relay. Such nodes will early run out of their energy. Moreover, CCS would cause large transmission delay due to multi-hop transmission through the long-distance chains [42]. Finally, relay CH is chosen based on the location of the CH and the residual energy of such nodes is omitted. This will result in energy hole in the network.

3) EBCRP

EBCRP (energy-balanced chain-cluster routing protocol) [43] is a distributed hierarchical algorithm with chain-cluster topology for WSNs. The routing scheme is based on the idea that each node delivers equal data and only short-distance communication is performed among different nodes. Only

neighbor nodes communicate with each other except CHs. The implementation of EBCRP can be partitioned into three phases: 1) chain-cluster formation; 2) cluster-head selection; and 3) steady-state. In the chain-cluster formation stage, the network is divided into multiple rectangular sections which are equivalent to different clusters, and a routing chain is created in each rectangular section by the ladder algorithm instead of the greedy algorithm. Thus, the long-distance communication is removed. In the cluster-head selection stage, several nodes act as CHs and communicate with the BS in rotation. The CH selection is performed according to the residual energy of different nodes. In the steady-state stage, the CHs, similar to the leaders of PEGASIS, collect and process data from other nodes along the cluster-chain and directly send data to the BS. This process is repeated until one node depletes its whole energy. At this point, the steady-state phase is ended. After that, a new round of tree construction, CH selection, and data transmission will begin.

The routing chain is constructed by the ladder algorithm rather than the greedy algorithm, so it balanced energy consumption to some extent. Besides, numbers of nodes in each chain were selected as CH in turn, so it can overcome the “hot spot” problem on some level. However, owing to the inflexible division of rectangular shaped areas, there exists long distance between two successive nodes. This may results in large energy consumption for long-distance communication. In addition, all CHs communicate with the BS directly. In large-region networks, data transmission between CHs and the BS needs too much energy consumption.

4) CHIRON

CHIRON (chain-based hierarchical routing protocol) [44] is a chain-based routing protocol with the goal of alleviating several flaws such as data propagation delay. This protocol consists of four operation phases: group construction, chain formation, leader election, and data transmission. In group construction phase, the network is divided into several fan-shaped areas. The BS sends control information to all nodes, and all nodes determine which group they respectively belong to. In chain formation phase, the node that is farthest away from the BS is initiated to create the group chain in each group. By using a greedy algorithm, the nearest neighbor node will be chosen to link the node, and become as the newly initiate node in next linking step. Leader node election is performed based on the maximum residual energy of group nodes. Initially, the node farthest away from the BS is assigned to be the group chain leader. Then, the node with the maximum residual energy will be elected the group chain leader. In data transmission phase, initially, data transmission is performed in each group along the chain to the chain leader. Then, the chain leaders collaboratively relay their aggregated data to the BS by leader-by-leader transmission manner.

Different from other chain-based routing protocols, CHIRON uses a short-haul and multi-hop data transmission style, which clearly decreases energy consumption for long-distance communication. Moreover, it can effectively reduce the chain length and redundant transmission paths, accordingly reduce the transmission delay. Nevertheless, different areas divided in this protocol are very uneven. This

results in imbalance of energy consumption and transmission delay. In addition, this protocol is not scalable, because the imbalance of energy consumption and transmission delay is a thorny issue with the increase of the network scale.

B. Tree-Based Hierarchical Routing Protocols

1) EADAT

EADAT (energy-aware data aggregation tree) [45] is an energy-aware distributed heuristic. The main goal of this algorithm is to tackle the problem of energy shortage by considering energy-aware data-centric routing. The algorithm is initiated from the sink by broadcasting a control message. The sink is assumed the root node in the aggregation tree. If a sensor node receives a control message for the first time, it sets up its timer which counts down when the channel is idle. The timer is associated with each sensor. The initial value of the timer is a decreasing function of residual power. In other words, the bigger the residual power, the smaller the value of the timer, the shorter the waiting time. During this process, the sensor chooses the node with the higher residual power and shorter path to the sink as its parent. When the timer times out, the node increases its value of hop count by one and broadcasts the control message. The result is an aggregation tree or a reversed multicast tree rooted at the sink. The tree can be re-constructed periodically. When the residual power of a node is below some threshold, an active sensor periodically broadcasts help messages and then shuts down its radio. After receiving the first help message from its parent, an active node switches to a new parent in the original tree, if it exists. Otherwise, it turns into a danger state.

One distinct advantage of EADAT is that sensors with higher residual power have a higher chance to become a non-leaf, which can perform more load burden. Moreover, mainly two factors, residual power and distance, are considered for path selection in this protocol, thus this protocol is not very complex. The sensor chooses the node with the higher residual power and shorter path to the sink as its parent, thus data transmission path may deviate from the sink very much. In this sense, the realistic path may be much longer than the minimal path from the source to the sink. Accordingly, it increases the energy consumption. In addition, the communication style suffers from large delay caused by the long distance data transmission path for the deviated routing.

2) BATR

BATR (balanced aggregation tree routing) [46] is a typical tree-based routing algorithm. Its goal is to find an optimal path based on a balanced tree, in which each node consumes the equal amount of energy. It is assumed that the BS is aware of the location information of all nodes in advance by special equipments such as GPS, and performs the task of routing computing. The routing algorithm begins with the BS as the root node, and then creates the relationship of parent and child with other nodes. This algorithm chooses the minimum weighted edge as much as the number of child nodes, and adds the new node to the tree. This means that data will be delivered from the node of the tree to the new node. When a neighbor node is found, the node is labeled as a leaf node. This process lasts until all nodes join in the routing tree. After several rounds

of energy dissipation, the BS updates the routing information by eliminating the dead nodes and recalculating the child nodes. In a summary, this routing algorithm constructs a minimum spanning tree with energy dissipation cost to achieve a minimum energy consuming system and extend the network lifetime.

The apparent merit of BATR is that energy expenditure is decreased to some extent by computing the minimum spanning tree with the cost functions of energy consumption. Moreover, energy expenditure of the routing tree is balanced by computing the number of child nodes according to the density of network. However, although the tree has almost the same number of child nodes below itself, residual energy of a node is not considered. This can't realize real energy consumption balancing. In addition, it is assumed that all nodes generate equal amount of data. This assumption is not very reasonable, in that it is not appropriate to on-demand applications.

3) PEDAP

Power-efficient data gathering and aggregation protocol (PEDAP) [47] is a tree-based routing protocol. The objective of PEDAP is to maximize the network lifetime, which is defined by the number transmission rounds. The minimum energy cost tree is used to data transmission. This tree is constructed by a centralized manner using Prim's minimum spanning tree algorithm. Initially, the sink is defined as the root of the tree. After that, the authors select the minimum weighted edge, one vertex of which is in the tree and another vertex is not in the tree. Such an edge is added to the tree. This process lasts until all nodes are merged into the tree. The total energy consumption in each communication round is achieved by computing a minimum spanning tree with link cost, which is related to data volume and transmission distance. In order to achieve load balancing among all nodes, the residual energy of the nodes is taken into account during the course of data aggregation. When data transmission is performed, the root of the tree structure acts as the CH. Each node receives data from its child nodes, aggregates the data with its own and delivers it to its parent node. This process continues until the aggregated data reaches the CH. Ultimately, the data is delivered from the CH to the sink.

PEDAP can cut down the total energy dissipation in each communication round by computing a minimum spanning tree with link cost calculation. Moreover, the residual energy is considered. This can contribute to load balancing to some extent. In addition, the transmission delay is lessened because the tree formation mechanism can reduce the path length. However, in large-scale networks, the energy cost calculation is a difficult task. So PEDAP suffers from the scalability problem. Furthermore, the robustness of PEDAP is very limited due to its centralized nature which requires the global knowledge of the location of all nodes at the sink.

4) ETR

ETR (enhanced tree routing) [48] is a typical tree-based routing scheme. ETR is an improvement of the tree routing (TR) [48], which is a simple routing protocol for a moderate tree-like network and follows only parent-child links starting from root node to leaf node. ETR was proposed to implement balance between performance and cost. In ETR, it is assumed that each

node has an updated neighbor table which has the address of its immediate one-hop neighbors. This neighbor table is important to identify the alternate path to the sink with the number of hops less than the actual path. ETR introduces an important parameter named network depth of a node, which represents the minimum number of hops from the node to the root node using only parent-child links. The network depth of the root node is 0, and the network depth of other nodes increases gradually. For data delivery among different nodes, each node has a unique identification number, which is initially assigned to the node. Each node on the tree route seeks to identify a proper neighbor node for the selection of the next hop. If such a neighbor node is found, the ETR route has a smaller hop-count. If no neighbor is identified at a node, the parent-child link is used.

In ETR, the performance of TR is improved by the neighbor table of nodes and structured address relationship. Moreover, by one-hop neighbor links, there is a decrease of the cost of storage and computation, as well as the energy consumption. However, the next-hop node is selected without considering the residual energies of neighbors. So, neighbors with low residual energy may afford much communication load. In other words, it may easily result in energy hole in the network. Furthermore, the shortest path tree or logical tree topology is used for data transmission, but when a node fails, the usual logical tree topology could not work again. Therefore, the robustness of this algorithm is limited.

C. Grid-Based Hierarchical Routing Protocols

1) PANEL

As a grid-based hierarchical algorithm in WSNs, PANEL (position-based aggregator node election protocol) [49], [50] uses the geographical position information of the nodes to determine the aggregators of the nodes. The most distinctive feature of PANEL is that it can satisfy both synchronous and asynchronous applications. In PANEL, the network is divided into several geographical clusters. A reference point is computed in each cluster by the nodes with respect to the position of the lower-left corner of cluster. The node that is the closest to the reference point is elected the CH. In the next epoch, the reference points and the CHs will be re-selected. There are two types of transmission manners, intra-cluster transmission and inter-cluster transmission. The intra-cluster transmission is to deliver a message to the aggregator of a specific cluster. It takes advantage of the communications within the cluster during the process of aggregator selection. The inter-cluster transmission is to deliver messages between the BS and distant clusters.

PANEL can achieve load balancing to some extent because each node acts as an aggregator with almost equal chances. Moreover, different from other data-aggregation based hierarchical algorithms, it supports asynchronous applications. However, it is a limitation that aggregation election is on the basis of the geographical information of nodes, which is difficult to obtain without special hardware and software conditions in many cases. In addition, if a cluster is partitioned, some nodes cannot hear the announcement of the node closest to the reference point, so another node will be elected as an

aggregator.

2) TTDD

TTDD (two-tier data dissemination) approach [51] is a grid-based protocol in which there exist multiple mobile sinks. Initially a grid structure is established when the network is divided into multiple cells with several dissemination nodes. Such dissemination nodes are responsible for relaying query message to proper sources. Whenever sinks require specific data, they query the whole network by a flooding manner until such queries are relayed to the source nodes. A source, at one crossing point of the grid, propagates data announcements to reach the other dissemination points by greedy geographical forwarding. When the message arrives at a node that is closest to the crossing point, it stops. This propagation process continues until the message reaches the boundary of the network. All sinks can move from one cell to another and each sink locally floods query messages within the cell to find the nearest agent node of the source. When a sink plans to move out of reach from communication with a primary agent node, it selects an immediate agent node which acts as a bridge between the primary agent node and the sink.

TTDD is better suited to event-driven applications rather than continuous traffic [52], because sources are queried on demand. However, a grid is constructed at the center of the source. So if events happen frequently, the control packets which construct a grid will increase, resulting in considerable energy depletion. Moreover, if a mobile sink moves fast, the path renewal cannot keep pace with the sink, causing severe performance degradation. In addition, TTDD is only for scenarios with fewer sources. With the rising of the number of sources, the signal overhead to construct structure increases.

3) HGMR

HGMR (hierarchical geographic multicast routing) [53] is a typical grid-based hierarchical protocol which combines the advantages of two previous location-based hierarchical protocols, GMR [54] and HRPM [55]. GMR is used to improve the forwarding efficiency while HRPM is used to reduce the encoding overhead. In HRPM, the whole network is hierarchically partitioned into multiple cells using the mobile geographic hashing idea. Each cell has an Access Point (AP) which manages the location information of the destinations in the corresponding cell. All APs are managed by an only Rendezvous Point (RP) of the network. There are two overlay trees, the Source-to-AP tree and the AP-to-Member tree, which are used for data transmission and constructed by the source. If a source has data packets to deliver, it forwards data to the highest level APs. Then, the highest level APs transmit such data to their local lower APs until such data arrives at the lowest APs. The lowest APs then unicast such data to multiple destinations.

In HGMR, different nodes play different roles, so such a data transmission method contributes to high energy efficiency. Moreover, the scalability problem is resolved by low overhead hierarchical decomposition since only manageable destinations exist in a cell. However, data transmission is concentrated on APs. Although APs work in rotation, this may result in unbalanced workload around such places. Additionally, data transmission is performed from the upper APs to the lower APs

hierarchically without considering the locations of the lower APs. This fixed transmission manner may increase the transmission path length and reduce the energy efficiency.

4) GMCAR

Grid-based Multipath with Congestion Avoidance Routing (GMCAR) [56] is a grid-based multipath routing scheme. In GMCAR, the network is divided into several grids, where each grid consists of a master node and multiple ordinary nodes. The master node has two tasks. One is to deliver data from ordinary nodes of the same grid, and the other is to forward data from other neighbor master nodes. Each master node has a routing table which stores multiple diagonal paths from the master node to the sink. Two important factors, grids densities and hop count, are taken into account for routing selection. According to traffic density of the grids, the network in GMCAR is also classified into two types of grids: boundary grids with low traffic and non-boundary grids with high traffic. GMCAR has two different routing schemes, multiple diagonal paths to the sink for the non-boundary grids, and a single path to the sink for the boundary grids. Furthermore, congestion mitigation is achieved by traffic sharing mechanism in which a secondary master node is selected.

GMCAR adopts two types of routing schemes for high traffic and low traffic respectively. This contributes to energy saving and network lifetime extension. Moreover, QoS is considered in GMCAR. So, this routing protocol has its advantages in terms of extending network lifetime, improving network throughput, reducing transmission delay, and etc. The main limitation of GMCAR is that each master node of every grid must be able to connect with a master node from a higher level grid. This can not keep up with the actual. Additionally, a node acts as a master node until its energy is about to drain. In this case, it starts an election process to select a new master node. This may easily result in energy hole in the network.

D. Area-Based Hierarchical Routing Protocols

1) LBDD

LBDD (Line-based Data Dissemination) [57] is a typical area-based routing protocol, in which the network is divided into two equal parts by a vertical strip or line of nodes. The nodes on this strip or line are referred to as inline nodes. This line acts as a rendezvous region for data storage and lookup. It assumes that each node knows its geographic location and network geographic boundaries. The operation of LBDD includes two main steps: dissemination and collection. In the former step, when an ordinary sensor node generates new data, it forwards the data to the nearest inline node. In the latter step, a sink sends a query to the line in a perpendicular direction. The first inline-node which receives this query propagates it in both directions along the strip or line until it reaches the inline-node storing the data. After that, the data is delivered directly to the sink.

The strip or line structure of LBDD is very simple and easy to realize by the source nodes and the sink [58]. Due to the simple topology, the communication way is also easy. However, this topology readily causes energy consumption imbalance, because only a trip or line acts as high-tier leader. If the wide of the line or strip is small, there exist load imbalance between the

line/strip and others. If the wide of the line or strip is large, there is load imbalance on the line or strip. Moreover, in large-region networks, the flooding on the line or strip will cause large energy consumption of nodes.

2) Ring Routing

Ring Routing [59] proposes a ring topology in which the ring consists of a one-node-width, closed strip of nodes that are called the ring nodes. After the formation of the ring, neighbor discovery is performed to determine the neighboring ring nodes. The ring acts as a rendezvous for the events and queries. The sink communicates with the ring by forwarding packets of its location information towards the network center by a follow-up manner, and the ring nodes conserve the current information of the sink at all times. The source nodes query the ring by a similar communication way. Moreover, the ring structure can be changed to prevent the ring nodes from dying quickly. So, the ring nodes must switch roles with regular nodes from time to time.

Similar to that in LBDD, the ring structure is simple and easy to construct. The problem of energy hole can be controlled to some extent because different nodes switch roles from time to time. The straightforward inquiry of fresh information of sink position from the ring contributes to fast data dissemination. The apparent drawback of Ring Routing is the overhead. The initial ring construction may cause high overhead in large networks. If the ring is large in large networks, data query around the ring may also cause too much overhead.

3) Railroad

A data dissemination architecture named Railroad was presented for large-scale WSNs [60]. This routing protocol proactively designs a virtual infrastructure called Rail which is a specific area where all the metadata of event data are stored. There is only one Rail which acts as a rendezvous area of the events and the queries. Rail is located in the middle area of the network so that each node can easily access it. Once a query is issued, it is delivered around Rail for relevant data stored in Rail. Once a relevant metadata appear, the source node of the data delivers such data to the sink which has issued the query. Queries issued by the sink travel on the rail by unicasts rather than broadcasts. This is the difference between Railroad and LBDD.

A sink can easily find all the required data by the help of Rail. The unicast query manner provides a simple structure to find data of interest. Moreover, Railroad system prevents Rail from becoming a bottleneck because Rail is designed sufficiently large [60]. However, similar to Ring Routing, if the ring is large in large networks, data query around the ring may also cause too much overhead. Furthermore, the expected data delivery delays of Railroad are higher than LBDD since the sink's queries have to travel through a longer distance [58].

4) VLDD

Virtual Line-based Data Dissemination (VLDD) [61] is proposed to achieve energy-efficient and reliable data transmission. VLDD designs a Virtual Line Structure (VLS) for data storage. The VSL is a specific area for data collection and information delivery. When a source node receives the

location information of a mobile sink group, it calculates the entry point of the VLS. If an entry node receives data packets from a source, it delivers the data to its neighbor node of the VLS. Then, the neighbor node transmits the data to its neighbor node of the VLS. Ultimately, the data reach the exist node of the VLS. When a sink in a group wants to obtain data packets from VLS, it sends a query packet toward VLS and follows one of two cases by the flag value, True or False. When a sink has False value in its flag, it means that the LS finished the group region calculation. Then, the sink obtains data packets from the VLS. When a sink has True value in its flag, it means that the LS collected the location information of sinks to calculate new actual group region. To process this case, two steps are performed. In the first step, the sink obtains the current location information of the actual sink group region from the LS agent. In the second step, the sink achieves the location of the new VLS and sends a query to the new VLS.

Similar to that in LBDD, the ring structure is simple and easy to construct. Compared with flooding-based transmission technique, VLDD can save energy consumption of sensor nodes and increase data delivery ratio. However, due to the line structure, long-distance routing from sources to the VLS may result in much energy depletion in large-area networks. Moreover, similar to Ring Routing, if the VLS is long in large networks, data dissemination around the VLS may also cause too much overhead and transmission delay.

V. COMPARISON OF DIFFERENT PROTOCOLS FOR WSNs

In the previous section, a few typical hierarchical routing protocols for WSNs have been discussed. In this section, the performance of different protocols is compared and the application scenarios of these protocols are summarized.

A. Comparison of Performance

According to a few important metrics, including mobility, energy efficiency, load balancing, scalability, etc., these atypical hierarchical routing protocols are compared in Table II. The details are analyzed as follows.

1) Energy efficiency

Due to long-distance communication between the chain leaders to the sink, large energy depletion is generated in chain-based routing protocols, including PEGASIS, CCS, and EBCRP. Thus, these routing protocols suffer from low energy efficiency. However, CHIRON uses a short-haul and multi-hop data transmission manner, which obviously decreases energy consumption for long-distance communication.

Long-distance transmission doesn't exist in tree-based topology, so the energy efficiency of this topology is improved compared with that of chain-based topology. BATR is a tree-based topology, but the energy expenditure is decreased to some extent by computing the minimum spanning tree with the cost functions of energy consumption.

The energy efficiency of grid-based topology is similar to that of tree-based topology. However, a grid is constructed at the center of the source in TTDD. If events happen frequently, too much control packets will result in considerable energy depletion. In HGMR, although energy efficiency is improved by role division among different nodes, data transmission is

performed from the upper APs to the lower APs without considering the locations of the lower APs. This may increase the transmission path length and reduce the energy efficiency.

Generally data query and data flooding exist in area-based topology, including LBDD, Ring Routing, Railroad, and VLDD. This may cause too much overhead and large energy consumption, especially in large-area networks.

2) Scalability

It is clear that long chain will result in large transmission delay, so chain-based routing protocols suffers from the problem of scalability. Especially, there exist only one chain in PEGASIS, so the problem of scalability of this protocol is very serious.

Tree-based topology, including EADAT, BATR, PEDAP, and ETR, suffers from large delay caused by too many communication hops, so this kind of topology shows its limitation of scalability.

In grid-based topology, including PANEL, TTDD, HGMR, and GMCARE, data dissemination is mainly performed among different grids instead of different nodes, so this contributes to the extension of the network. Especially, the scalability problem of HGMR is further improved by low overhead hierarchical decomposition since only manageable destinations exist in a cell.

As mentioned before, generally data query and data flooding exist in area-based topology, including LBDD, Ring Routing, Railroad, and VLDD. This will result in too much overhead and large energy expenditure, especially in large-area networks. In other words, there exist the problem of scalability.

3) Delivery delay

In chain-based topology, such as PEGASIS, CCS, and EBCRP, the long chain structure suffers from large transmission delay. However, the chain-based routing protocol CHIRON uses a short-haul and multi-hop data transmission style, which can effectively reduce the chain length and redundant transmission paths, accordingly reduce the transmission delay.

Tree-based routing protocols, such as EADAT and BATR, suffer from large delay caused by the long distance data transmission path. In PEDAP, the transmission delay is lessened due to the fact that the tree formation mechanism can reduce the path length. Moreover, ETR introduces an important parameter named network depth of a node, which represents the minimum number of hops from the node to the root node using only parent-child links. This can reduce the transmission delay to some extent.

In grid-based routing protocols, such as PANEL, HGMR, and GMCARE, data dissemination is performed from one grid to another, rather than from node to another. This can reduce transmission hops and transmission delay. However, the path of data transmission in TTDD is not the shortest path, thus it may lead to large latency for the long path.

As mentioned before, there exist data query and data flooding in area-based topology, including LBDD, Ring Routing, Railroad, and VLDD. This will increase the transmission delay. Furthermore, it's mentioned before that the expected data delivery delays of Railroad are higher than LBDD due to the long-distance traveling of the sink's queries.

Additionally, if the VLS in VLDD is long in large networks, data dissemination around the VLS may also cause large transmission delay.

4) Load balancing

In chain-based routing protocols, including PEGASIS, EBCRP, and CHIRON, although nodes near to the leaders have much more communication load, all nodes act as the leader in turn. This can achieve load balancing to some extent. However, energy expenditure in CCS is not balanced because data delivery uses a relay style and the tracks closer to the BS have more data to relay.

As a tree-based topology, PEDAP can contribute to load balancing to some extent, due to the residual energy is considered. However, BATR and ETR can't realize real energy consumption balancing, because residual energy of nodes is not taken into account.

As a grid-based topology, PANEL can achieve load balancing to some extent because each node acts as an aggregator with almost equal chances. In TTDD, due to mobile sink which collects data throughout the network, data transmission can be performed throughout the network, so the communication load can be balanced. However, data transmission is concentrated on APs in HGMR. Although APs take turn to work, this may result in unbalanced workload around such places. Moreover, a node acts as a master node until its energy is about to drain in GMCAR. This clearly results in imbalanced energy consumption.

In LBDD, only a trip or line acts as high-tier leader, and there exist load imbalance between the line/strip and others. If the wide of the line or strip is large, there exist load imbalance on the line or strip. In VLDD, due to the line structure, long-distance routing from sources to the VLS may result in much energy depletion and imbalanced communication load in large-area networks. However, the load balancing is improved to some extent in Ring Routing, because different nodes switch roles from time to time. Moreover, Railroad system prevents Rail from becoming a bottleneck because Rail is designed sufficiently large [60].

5) Algorithm complexity

As a chain-based topology, PEGASIS assumes that all nodes achieve global knowledge of node positions to select closest neighbors. This is a complex operation course. Moreover, the data transmission in long chain increases the algorithm complexity. Nevertheless, in CCS, EBCRP, and CHIRON, no global knowledge is needed and data depletion is limited in a smaller area. Accordingly, the algorithm complexity of these protocols is decreased.

In the tree-based protocol of BATR and PEDAP, although energy expenditure is decreased to some extent, this pays the price of computing the minimum spanning tree with the cost functions of energy consumption. Clearly the algorithm complexity is increased compared with that of EADAT and ETR.

In PANEL, the aggregation election is on the basis of the geographical information of nodes, which needs special hardware and software conditions. So this results in high algorithm complexity. In GMCAR, Each master node has a routing table which stores multiple diagonal paths, and two

TABLE II
COMPARISON ON DIFFERENT ATYPICAL HIERARCHICAL ROUTING PROTOCOLS FOR WSNs

Protocol	Classification	Control manner	Mobility	Data aggregation	Energy efficiency	Scalability	Delivery delay	Load balancing	Algorithm complexity	Implementation cost
PEGASIS	chain-based	centralized	no	yes	very low	very low	very large	moderate	high	low
CCS	chain-based	distributed	no	yes	very low	low	large	bad	moderate	low
EBCRP	chain-based	distributed	no	yes	very low	low	large	moderate	moderate	low
CHIRON	chain-based	distributed	no	yes	moderate	low	small	moderate	moderate	low
EADAT	tree-based	distributed	no	yes	moderate	low	large	moderate	low	low
BATR	tree-based	distributed	no	yes	low	low	large	bad	moderate	low
PEDAP	tree-based	centralized	yes	yes	moderate	low	moderate	good	moderate	large
ETR	tree-based	distributed	no	yes	moderate	moderate	moderate	bad	low	low
PANEL	grid-based	distributed	no	yes	moderate	moderate	moderate	good	high	very large
TTDD	grid-based	distributed	yes	yes	very low	moderate	very large	good	low	large
HGMR	grid-based	distributed	no	yes	low	high	moderate	bad	low	low
GMCARE	grid-based	distributed	no	yes	moderate	moderate	moderate	bad	high	large
LBDD	area-based	distributed	yes	yes	moderate	moderate	moderate	low	moderate	large
Ring Routing	area-based	distributed	yes	yes	moderate	moderate	moderate	good	moderate	large
Railroad	area-based	distributed	yes	yes	moderate	moderate	large	good	moderate	large
VLDD	area-based	distributed	yes	yes	moderate	moderate	large	low	moderate	large

important factors are taken into account for routing selection. This clearly increases the algorithm complexity.

6) Implementation cost

Most routing protocols need low implementation cost. Geographical position information of the nodes is needed in PANEL, in which this is a restriction because the achievement of geographical position needs special condition, such as GPS-like hardware and software. Moreover, PEDAP suffers from the same cost problem.

TTDD, LBDD, Ring Routing, Railroad, and VLDD use a mobile sink to collect data throughout the network, so this increases the implementation cost to some extent.

As mentioned before, in GMCAR, Each master node has a routing table which stores multiple diagonal paths, and two important factors are taken into account for routing selection. This also increases the implementation cost.

B. Comparison of Application Scenarios

To meet the increasing demand of choice and diversity of applications [62], the application scenarios of these atypical hierarchical routing protocols can be concluded. According to the detail analysis of different atypical protocols in Section IV and the detailed performance analysis of these protocols in Section V, the detailed application scenarios of these routing protocols are summarized in Table III.

VI. OPEN ISSUES

It is apparently seen so far that significant efforts have been made in designing effective hierarchical routing protocols for WSNs based on different topologies. However, there is a high potential to improve current routing methods in the future. A few important open issues are summarized as follows:

TABLE III

COMPARISON OF APPLICATION SCENARIOS OF DIFFERENT PROTOCOLS

Protocol	Application scenario
PEGASIS	Small-range networks
CCS	Small-range networks
EBCRP	Small-range networks
CHIRON	Small-range networks
EADAT	Data-centric based and small-range networks
BATR	Proactive networks
PEDAP	Small-scale networks
ETR	Small-scale networks
PANEL	Synchronous and asynchronous applications
TTDD	Networks with multiple mobile sinks
HGMR	Multicast applications
GMCARE	QoS based networks
LBDD	Mobile sink networks
Ring Routing	Mobile sink networks
Railroad	Large-scale networks with mobile sink
VLDD	Mobile sink networks

(1) It is a pioneering attempt to design a combination of multiple topologies for a specific hierarchical routing protocol in WSNs. For instance, implementing cluster-based topology with the assistance of grid-based topology for hierarchical routing is an open issue.

(2) Further research would be needed to design cross-layer routing protocols in WSNs. For example, physical layer and MAC layer can realize transmission range adjustment and

communication collision avoidance, which can facilitate routing designing in network layer.

(3) It is a tendency to adopt multiple sinks and mobile sinks in WSNs, for the sake of energy efficiency increase, energy hole avoidance, and network lifetime extension. However, this easily results in great information flooding by multiple sinks and mobile sinks. Further research should be done to minimize the control overhead.

(4) Every type of topology has specific advantages and drawbacks, and how to aggregate different types of topologies and merge their advantages is still a challenge.

VII. CONCLUSIONS

WSNs have attracted increasing attention in recent years for their extensive applications. Due to the limited resources, routing is full of challenges in WSNs and logical topology plays a crucial role in routing design of resource-constraint networks. In the past, much effort has been made in designing effective hierarchical routing protocols for WSNs based on different logical topologies.

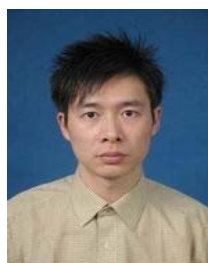
In this paper, a survey of logical topologies and hierarchical routing is provided. More specifically, hierarchical routing for WSNs is divided into five categories, including cluster-based, chain-based, tree-based, grid-based, and area-based topologies. Moreover, different logical topologies for hierarchical WSNs have been analyzed according to different logical topologies, including their characteristics, advantages and disadvantages. Additionally, various hierarchical routing protocols for WSNs have been discussed in detail. After that, hierarchical routing protocols for WSNs have been compared according to several performances. Finally, some open issues have been pointed out.

We hope that this survey not only provides a more expansive understanding of logical topologies and hierarchical routing for readers, but also helps researchers and system designers to select appropriate logical topologies and hierarchical routing protocols for their specific applications.

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