Multipath Routing Techniques in Wireless Sensor Networks: A Survey

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Kewei Sha

University of Houston - Clear Lake

Robert Allen Greve

Oklahoma City University

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Kewei Sha, Jegnesh Gehlot and Robert Greve

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Abstract Multipath routing is an efficient technique to route data in wireless sensor networks (WSNs) because it can provide reliability, security and load balance, which are especially critical in the resource constrained system such as WSNs. In this paper we provide a survey of the state-of-the-art of proposed multipath routing protocols for WSNs, which are classified into three categories, infrastructure based, non-infrastructure based and coding based, based on the special techniques used in building multiple paths and delivering sensing data. For each category, we study the design of protocols, analyze the tradeoff of each design, and overview several representing protocols. In addition, we give a summery of design goals, challenges, and evaluation metrics for multipath routing protocols in resource constrained systems in general.

Keywords Wireless Sensor Networks · Multipath Routing · Survey

1 Introduction

A wireless sensor network (WSNs) consists of a large number of light-weight sensor nodes having limited battery life, computational capabilities, storage, and bandwidth. These low-cost sensor nodes can be deployed either randomly by dropping from an airplane or precisely using manual deployment. These sensor nodes sense a change in the environmental or a physical quantity and transmit this data to the base station, also referred to as a sink node. The sink node is usually a powerful machine like a Laptop or a Desktop [48, 29].

Kewei Sha
E-mail: ksha@okcu.edu

Jegnesh Gehlot
E-mail: jgehlot@my.okcu.edu

Robert Greve
E-mail: rgreve@okcu.edu

This emerging technology has been adopted by many fields as a promising solution to numerous challenges. For example WSNs is used in remote sensing, real-time traffic monitoring [60], weather monitoring, military surveillance [6], health care [5], civil structure monitoring [57], forest fire detection [20], fire rescue [39] and many other areas [17]. In large scale WSN, the nodes are located far from the sink and therefore use the intermediate nodes to route the data packet towards the sink. Routing in WSNs is very important and it is distinguished from other networks due to the following characteristics [1, 2]:

- An IP-based scheme is difficult to be applied in WSNs, because of limited available resources and an extremely large scale.
- Unlike traditional routing protocol, in WSNs, most traffic is routed from nodes to the base station.
- In WSNs, the nodes are resource constrained in terms of energy, storage, and computational capacity. Efficient use of resources is essential.

There are mainly two types of routing techniques, single path routing and multiple path routing. Single path routing is simple and scalable, but does not efficiently satisfy the requirements of resource constrained WSNs. It is simple because the route between the source node and the destination node can be established in a specific period of time. It is scalable because, even if the network changes from ten nodes to ten thousand nodes, the complexity and the approach to discover the path remains the same. While considering the characteristics of a WSNs, single path routing is not efficient for the following reasons.

- In single path routing, it is easy for the source node to select the intermediate data routing nodes from the same part of the network over and over again. This may cause depletion of power of those sensor nodes and network partition, which shortens the lifetime of WSNs.
- In WSNs, failures are common because of insufficient power, limited storage space, unreliable wireless communication, or unpredictable environmental interference. If any failure occurs, most single path routing protocols could not successfully deliver sensed data to the sink due to a lack of fault-tolerance mechanisms.
- In single path routing, the presence of a malicious node on the path can manipulate and corrupt the data without catching the attention of the sink node.

Multipath routing is an alternative routing technique, which selects multiple paths to deliver data from source to destination. Because of the nature of multipath routing that uses redundant paths, multipath routing can largely address the reliability, security and load balancing issues of single path routing protocols. Thus, multipath routing plays an important role in WSNs and many multipath routing protocols have been proposed in the literary of WSNs research. In this paper, we take an initial step to summarize all multipath routing techniques proposed in the WSN research literary. On the basis of the protocol feature and its specification we classify existing multipath routing techniques into three categories: *A) Infrastructure Based*, *B) Non-Infrastructure based*, and *C)Coding Based*. The major concern of the protocols within category A is to construct and maintain specific multipath infrastructure by considering location and resource capabilities. Protocols which do not build any specific infrastructure and decide the next hop on the basis of its local knowledge are classified into category B. The category C protocols use variant kinds of coding schemes to fragment the data packet at the source node and then send the chunks through discovered multiple paths.

Besides this survey, because of the importance of routing protocols, there are also several survey papers discussing routing protocols in WSNs [1, 2], but to the best of our knowledge, there is no such dedicated survey for multipath routing protocols. Furthermore, the scope of the survey presented in this paper is different from others. Within the exception of a summary of the design of previous multipath routing protocols, we provide an extensive analysis of the challenges and metrics in designing multipath routing protocols. Writing a comprehensive survey of the multipath routing techniques, we hope that this paper will serve as a good reference to those who are interested in multipath routing protocols. Furthermore, we hope this paper will provide merit to and trigger the design of more sophisticated multipath routing protocols, not only for WSN, but also for any critical systems built based on unreliable components, including Cyber-Physical Systems [53] and Smart Grids [23].

The rest of the paper is organized as follows. In Section 2 we discuss and explain how multipath routing plays a significant role in WSNs and can work efficiently in the presence of resource constraints including limited energy, storage, and computational capacity. In Section 3 we summarize a set of challenges in implementing a multipath routing scheme by considering the special features of WSN. Section 4 describes a set of common evaluation metrics, on the basis of which we evaluate the performance of multipath routing protocols. In Section 5 we classify the existing multipath routing protocols into three categories and introduce representing protocols of each category in detail. Finally, related work is listed in Section 6 and we draw conclusions in Section 7 respectively.

2 Advantages of Multipath Routing

In a wireless sensor network, the sensor nodes are resource constrained. Effective and efficient usage of the available resources is a big challenge in sensor networks. Several routing protocols have been proposed for WSNs [1, 2], many of which adopt single path routing techniques and suffer from many problems as we discussed in the previous section. With the help of multipath routing we can use the available resources at each node more efficiently. Multipath routing can overcome significant drawbacks of a single path routing scheme because it can provide reliable data transmission, even distribution of network traffic, and data security. Next, considering the characteristics of WSN, we enumerate the major advantages of multipath routing protocol over single path routing.

1. Data Reliability. Data Reliability can be defined as the ratio of the amount of data received by the destination node to the amount of data sent by the source node. Protocols using a single path to transfer the data from source to destination have low data reliability. This is due to various factors including environmental interruption, faulty nodes, and resource constraint. Sometimes, heavy propagation of data packets can cause network congestion which may also lead to significant data packet loss [41]. On the other hand using multipath routing increases data reliability by sending the data along multiple redundant paths [33]. Even if some paths fail, the data will have a very high probability to be received by the destination node. In addition, the multipath routing approach is used to recover from failures. For example in [16] the authors propose a novel scheme, HREEMR, which constructs braided multipaths to enable energy-efficient recovery from failures. Finally, multipath routing helps load balance to avoid network congestion, which improves data reliability.

2. Data Security. In single path routing, if any sensor node on the path is compromised into malicious activity, then the network is not safe to transmit the data. Single path routing is prone to several types of attacks. For example, a sink hole attack can be launched to single path routing in which the attacker tries to divert the network traffic from a specific area through a malicious node. Selective forwarding is another type of attack to the single path routing protocol, in which the malicious node simply drops the forwarding packet [25].

Multipath routing can improve security because of the nature of multiple paths. When data is sent from multiple paths, even in the presence of malicious paths, we can get the original data to the receiving end by using reliable paths. With the help of multipath routing, the malicious attacks can be counter measured by increasing the confidentiality and robustness of transmitted data. Moreover, by incorporating the coding technique with multipath routing, the data can be transmitted in an encoded form and only decoded at the destination node, which prevents eavesdrop on the sensing data during transmission. This approach is efficient and is an ideal mechanism in a resource constrained environment because it requires much less energy in encoding and decoding than in communications.

3. Energy-Efficient. Wireless sensor nodes have limited energy supply, therefore efficient use of energy is necessary to maximize the network lifetime. In the single path routing protocol the usage of the same optimal path over and over again may cause certain nodes to deplete their energy at a faster pace, which may cause network partition.

Load distribution using multipath routing helps to improve the network lifetime by delaying the appearance of network partition, although more data could be transmitted than that using single path routing. To control the duplicated transmission of the same data via multiple paths, various coding techniques can be used. Using coding techniques, the original data will be fragmented into pieces and those fragments, instead of the whole data, are transmitted through different paths. Thus, load can be distributed to multiple paths and each path transmits much less data compared with an optimal single path. In this way, coding techniques control the increased volume of the total transmitted data and extend the lifetime of WSNs.

When considering the same level of reliability, multipath routing can be more energy-efficient. In single path routing, acknowledgement and retransmission must be implemented to achieve high reliability. This adds extra communication overhead. In multipath routing, to achieve the same level of reliability, with the help of network coding and multiple paths, acknowledgment and retransmission can be avoided, decreasing message overhead and providing a longer network lifetime.

3 Challenges in Building Multipath Routing Protocols

In WSNs, due to the short transmission range between the nodes, multi-hop routing is used to transfer the data to the sink. Therefore to route the data packet from source to destination, it uses many intermediate nodes which act as data routers. Routing in wireless sensor network is a big challenge because of availability of fewer resources at each node, deployment of network in challenging and hostile environments, frequent change in network topology and fault-tolerance [1]. To tolerate failure, in single path routing, an optimal path is selected to route the data from source to destination, and an alternative path is used when an optimal path fails. In multipath routing, multiple paths are discovered to distribute the network traffic and prolong network lifetime; however, there are several major questions to be addressed in the design of multipath routing protocol. These questions are like follows.

1. How many paths are optimal?
2. How does one discover those optimal paths?
3. How does one maintain discovered paths and distribute the data among those paths?

Many algorithms utilizing intelligent techniques and different design principles have been proposed in the search for answers to these questions. However, it remains a challenging task. Thus, multipath routing has many advantages in wireless sensor network as mentioned in Section 2 but these advantages come with some challenges as listed as follows.

1. Number of Routes. In multipath routing, reliability and security are functions of the number of paths selected for transferring data from source to destination. If there is not a sufficient number of paths available between source and destination, achieving the goal of multipath routing is not possible. Discovery of multiple paths from different portions of a network helps in distributing the network traffic evenly. This will increase network lifetime but at the cost of extra route establishment time. However, variant coding schemes could be used in order to make the data transmission more secure and more energy-efficient [54,15,51,40]; however, the implementation of these schemes is primarily based on the number of routes discovered between source and destination. Moreover, in multipath routing the traffic increases significantly due to transmission of the same data from different discovered routes. Therefore, a tradeoff must be made between the reliability, security and energy efficiency when considering the number of paths in the multipath routing protocol.

2. Route Discovery. The nodes in the WSN act as data sender as well as data router. Once the data packet has arrived at an intermediate routing node, it must select the next node having the capability of passing the data packet in the direction of the sink. The selection of the next node is based on gradient information including signal strength, residual energy and others. Along with the gradient information, the source node has to verify that the selected node is not a malicious node, which causes extra message overhead and transmission delay [4]. In building the infrastructure containing capable neighbors, an intermediate node has to exchange messages. If a certain discovered path fails in the middle and the sink or source node has to initiate the path construction phase, it results in extra message overhead. The selected data routing nodes directly affect the Quality of Service (QoS), while it is difficult to find a set of optimal multiple paths balancing the energy consumption and the quality of routing. The route discovered by the protocol can be either node disjoint, link disjoint or non-disjoint routes [33]. Disjoint path provides higher fault-tolerance as compared to non-disjoint paths but is more difficult to be discovered [33]. In the case of a high dynamic sensor network the route discovery process is even more challenging because of continual topological changes.

3. Consumption of Resources. In WSN the efficient resource consumption at each node is necessary in order to increase the network lifetime. In multipath routing many messages are exchanged among nodes in order to discover the optimal paths between source and destination. Once the multiple paths are discovered, the data packet will be transferred from source to destination using those multiple paths. Transferring data packets from different portions of the network helps in distributing the traffic to the whole network, while it is a challenge to design an intelligent algorithm to distribute the traffic evenly to the whole network. To overcome the issue of sending the same data packet from different discovered paths, various coding schemes can be used. Coding schemes fragment the data packets and send the fragments through different discovered paths. This scheme saves transmission and receiving energy, but it needs extra computation at each node and path maintenance. The successful implementation of the coding technique also depends on the number of paths discovered and number of fragments received at the destination node. If there is less than the necessary number of data packets delivered at the destination, then the original data cannot be recovered. Moreover, robustness and compression efficiency of the coding technique are also of major concern when using coding techniques. Therefore a tradeoff exists between reliability and energy efficiency.

4. Path Maintenance. In multipath routing, the usage of multiple paths from source to destination needs to be maintained periodically in order to achieve high data reliability as well as load balance among multiple paths. If the path is broken, then the source node has to select another optimal path. The selection of the best next hop is based on heuristic information. Collection of all heuristic information is challenging and can cause delay in data packet transmission. The decision of path maintenance can be made by the destination node or it is set up in the application itself. In some cases only few optimal paths are used from several discovered multiple paths. In such a scenario some unnecessary messages are transmitted to unused paths in order to keep them alive. This may cause extra message overhead and consume more energy. Thus, the efficient and effective maintenance of multiple paths is a big challenge in multipath protocol design.

4 Major Performance Metrics

In this section we present the metrics on the basis of which we can evaluate the performance of protocols using a multipath routing approach in a WSN. We focus on metrics to evaluate the advantages and overheads of those protocols.

1. Energy Efficiency. Energy efficiency should be one of the major design goals of any routing protocol in WSN. Network lifetime [38,37] integrating energy consumption in sensing, computation and communication, as well as network coverage and connectivity can be used to evaluate energy efficiency of multipath routing protocols. On the other hand, because the most significant energy consumption of sensors is in communication, the total number of messages transmitted in multipath protocols can also be a good metric to evaluate energy efficiency. Moreover, energy efficiency in routing protocols is largely related to load balance performance of the evaluating protocol, because load balancing helps to extend the lifetime of sensor networks and saves the network from network congestion. Thus, any metrics that can be used to evaluate load balance could be applied for this purpose.

2. Data Reliability. Reliability is one of the most important advantages of multipath routing protocol over single path routing protocol. Data reliability is computed as the total number of messages received at the destination node divided by the total number of messages initiated from the source node. In other words we can define data reliability as the percentage of data packet successfully received by the destination node. The reliability of a protocol is also affected by the number of paths discovered, because this effects the amount of data transmitted. Therefore, the more paths discovered, the greater the data reliability.

3. Route Setup Time. Compared to single path routing protocols, path discovery is more challenging in multipath routing protocols. The metric, route setup time, is usually used to evaluate the overhead of multipath routing protocol. The route setup time can be defined as the total amount of time taken by the sink or source node to discover the paths from the source to the destination node. The better the protocol design, the lesser the route setup time.

4. Average Delay. Because of the consideration of load balance and reliability, multipath routing could take a longer path than single path routing. As a result, it may take longer for a packet be transferred from source to destination. We use average delay to evaluate the delay caused by multipath routing. Average delay can be defined as the total amount of time taken by the data packet to travel from source to destination. Delay in data packet arrival at the destination node can be caused by heavy computation at intermediate nodes or network traffic. Thus, to evaluate average delay, we can also use another metric, routing path length, which is defined as the average path length of multiple paths in multipath routing, because delay is largely related with the path length. In addition, routing path length can reflect the energy efficiency performance of the routing protocol.

Figure 1 summaries two sets of performance metrics presented above. One set is used to evaluate the advantages of the multipath routing. The other set is used to evaluate the overheads of multipath routing. In this paper, the reviewed multipath routing protocols will be compared qualitatively based on the proposed metrics in Figure 1.

Performance Metrics		
Advantages		Overheads
Energy Efficiency	Lifetime (LFT) Load Balancing (LB)	Route Setup Time (RST) Amount of Traffic (TF) Average Path Length (PLen) Average Delay (Delay)
Reliability	Packet Delivery Rate (PDR) Number of Paths (NoP)	

Fig. 1 Performance metrics for multipath routing protocols.

5 Overview of Multipath Routing Protocols

The main purpose of the multipath routing approach is to achieve data reliability, security and load balancing. Achieving all these goals in the resource constrained and often randomly deployed WSNs, is quite a challenge. Various techniques have been proposed in efficient multipath routing protocol design, for example, network coding is used, where data at the source node is fragmented and transferred into chunks to different discovered paths, and controlled flooding is used to find proficient neighbors. There are also many heuristic multipath routing protocols proposed to establish multiple paths based on energy budget or the distance to the sink.

In this paper, we classify the existing multipath routing protocols into three categories as shown in Figure 2. The rationale behind such a classification is to categorize the protocols on the basis of the design and the technique used in discovering multiple paths and transferring data. Infrastructure based multipath routing protocols try to discover and maintain multiple paths from source to destination before data transmission, and all data are transmitted via those discovered multiple paths. In contrast, non-infrastructure based multipath routing protocols do not try to establish and keep multiple paths; instead, they forward data to multiple next hops based on the local heuristic knowledge. Finally, we classify all protocols using different types of coding or data fragmentation techniques, into the category of coding based routing protocols. Next, we give the design principle and a list of representing protocols in each category.

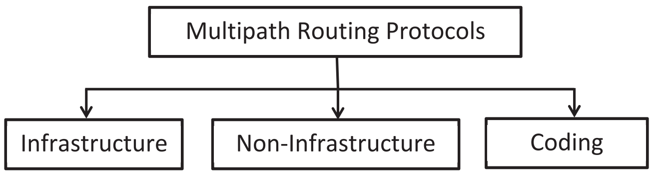

Fig. 2 Classification of multipath routing protocols.

5.1 Infrastructure Based Multipath Routing Protocol

The most important features of the infrastructure based multipath routing protocol is the construction and maintenance of multiple paths from source to destination. Any specific topology structure can help to build an efficient route from source to destination. For example, in a spanning tree, in which the WSN is considered to be organized into a tree and the sink node acts as a root of that tree, multiple paths are discovered by traversing the tree. To design an infrastructure not based on a specific topology structure, protocols use message broadcasting which helps them to collect information about their neighbors. Each node stores a list of capable neighbors which can efficiently transfer the data. Then, on the basis of heuristic information such as node's location, position in the structure and capability, multiple paths are discovered. These discovered paths are usually node-disjoint paths, which help to avoid data collision and interference.

An infrastructure provides reliable and fast data transmission because every intermediate data routing node has its next hop set up in advance. It also provides the protocol reducing failure recovery time by assigning the alternative route, which is also discovered in advance. Building an infrastructure is not enough to create an optimal multipath routing protocol. To achieve reliability, security, and load balancing, protocols use different techniques. Therefore, on the basis of the technique used by the protocol to build multiple paths, we further divide this category into three sub-categories: energy-aware, hierarchy-based and ant-based.

5.1.1 Energy-aware Multipath Routing Protocols

Energy-aware multipath routing protocols are mostly heuristic protocols that pick up the next hop primarily based on the remaining energy of neighboring nodes. Because sensor nodes have very limited amounts of energy, and in order to prolong the network lifetime, energy-aware approaches avoid choosing sensors with low energy in data forwarding. This presents network partition, because of early energy depletion of a part of sensors. Therefore, it is a good heuristic in balanced efficient routing protocols. Moreover, these protocols aim to balance the communication load based on the remaining energy of sensor nodes to balance energy consumption and provide data reliability using multiple paths.

The protocols in this category construct the routes by broadcasting messages to whole network. The main purpose of message broadcasting is to collect information of the neighboring nodes and to build the neighboring table. Each node contains a neighboring table which stores the significant information about the neighboring nodes including residual energy, hop distance, and signal strength. The neighboring table helps the node to decide the best next hop by using the attributes stored in the table. This scheme leads to a multiple-path infrastructure, which is created from the nodes that satisfy the specific requirements. Energy-aware protocols use reactive routing, meaning that the path is created only when it is required. This reduces much of the communication overhead. Path maintenance is another major concern for every multipath routing protocol. In order to keep track of path performance or path failure, the destination node monitors the inter-arrival delay for each data packet. If the delay is above a predetermined threshold, the sink will assume that the path is broken. In the following we present several representing protocols in this category, followed by a list of open problems.

In [30] the author proposes an effective algorithm, EEMR, to discover node-disjoint multiple paths between the source node and the destination node. Multiple paths are constructed by considering a link cost function, which takes both energy level and hop distance into account. The author also presents a load balancing algorithm, which helps to distribute the network traffic evenly onto the whole network. Load balancing is achieved based on the definition of the load balancing ratio (ϕ), which is:

$$\phi(\bar{r}) = \frac{(\sum_{j=1}^{N} r_j p_j)^2}{N \sum_{j=1}^{N} (r_j p_j)^2} \tag{1}$$

Where, N is the number of disjoint paths between the source and the sink, and p_j is the product of the path cost, which is the sum of the individual link costs along the path j. $\bar{r}$ is the traffic allocated to the available routes and r_j is the traffic allocated to the path j. When the load balance ratio reaches 1, the traffic is considered balanced. Moreover with the successful delivery of each data packet the sink node will retrieve the current condition of the multiple paths in use, which helps in distributing the data over the paths.

By using the link quantity as a performance metric the authors in [21] propose a multipath routing protocol, QoS and energy-aware multipath routing (QEMPR) for real-time application in WSNs. Each node in the network is assigned with a unique ID and also has a capability of calculating the packet receiving and packet sending probability using the link quality information. The multiple paths are discovered by message broadcasting and each node maintains a neighboring table which stores the information about the neighboring node such as remaining energy and transmission range. After constructing the paths, the packet will be transmitted based on the packet sequence number and number of hops it is away from the sink. This means the source will first transmit the packet with the lowest sequence number through the path with the lowest hop number. Then the packet sequence number and the hops associated with the path go higher and higher. In this way the sink will receive the packet consecutively. This approach helps to distribute the network traffic throughout the multiple paths, thus increasing network lifetime.

In [48], the authors propose EEAMR which focuses on distributing the traffic based on the node's residual energy and received signal strength. For consistent resource utilization, more load is assigned to under-utilized paths and less load is assigned to over-utilized path. In order to save more energy, nodes which are not participating in the data transmission go into sleep mode.

In another paper [49] authors propose a multipath routing protocol named Reliable and Energy Efficient multipath routing protocol (REEM) which constructs multiple paths from source to destination, considering node reliability and energy level. The path is constructed by a base station through message broadcasting and each receiving node will store the neighboring information in a table. Also, the path reliability is evaluated by the base station through a weighted and oriented graph, based on the neighbor information.

It is more challenging to be energy-efficient in large scale WSNs. Therefore the authors in [7] propose a novel protocol named Multipath Routing in large scale sensor networks with Multiple sink nodes (MRMS) to save energy. The main idea is to deploy multiple sink nodes and uses path cost metric to select the multiple paths. The path cost metric is defined based on the distance between two neighbor, hop count and available energy at the node.

In some scenarios the WSN is deployed in such an environment where the base station needs to query a certain portion of the network to collect the sensing information from the nodes. Y. Chen and N. Nasser in [61] propos an energy balancing multipath routing protocol (EBMR) which is based on client-server architecture with the base station processing the data received from the sensor nodes. The path construction is done by using message broadcasting from the base station. Each node in the network contains a neighboring table. Whenever the base station needs to query some data in the network it broadcasts a Data Enquiry (DE) message. The nodes which have the required data will reply back with a Data Enquiry Reply (DER) message. Upon receiving the DER message, the base station will calculate the shortest path to the source node by calculating the amount of energy consumes in transmitting the package from source to base station.

The above mentioned protocols succeed in presenting an intelligent and adaptive energy-aware multipath routing approach. However, there are still several concerns. Firstly, message broadcasting or flooding to the whole network introduces large communication overhead. Secondly, sending the same data packet from different discovered paths consumes a lot of energy at each data routing node and increases the network traffic significantly. Finally, above mentioned energy-efficient multipath routing protocols are prone to malicious attacks. For example, these protocols use message broadcasting in order to announce themselves to the neighbors. If node A receives a message from node B, which declares to have high residual energy and high signal strength, it can cause node A to select node B as the next data routing node; however, node B can be an adversary, which broadcasts the information with a high transmission power and could convince the nodes to become its primary neighbor. This will lead the network traffic into a confusing state and impact network reliability and security. This type of attack is called "HELLO flood attack" [25].

5.1.2 Hierarchy Based Multipath Routing Protocols

Hierarchy based multipath routing protocols focus on building the infrastructure in which nodes build a hierarchical relationship in order to discover efficient multiple paths. Hierarchical infrastructure has many advantages in WSNs. Firstly, it is appropriate for a large scale network because the communication overhead can be significantly reduced due to the hierarchy. Secondly, it prolongs the network lifetime by assigning the heavy workloads, such as selecting nodes, sending and receiving data, to the nodes with more residual energy, and sending simple tasks to the low energy nodes. Hierarchy is constructed by broadcasting the route update messages. The hierarchy is built on the basis of the sequence of receiving messages. Hierarchal protocols construct node disjoint paths to avoid collision. The major difference between hierarchy protocols and energy-aware based protocols is that, in hierarchy based protocols the next hop is selected on the basis of the hierarchal relationship built during message exchange. While in energy-aware based protocols the next hop is selected from a group of neighboring nodes, based on their energy level. The protocols in this category are described as follows.

In [29], the authors propose a special protocol, N-to-1 which discovers multiple paths from each node in only one route discovery process. For path discovery the base station periodically broadcasts the route update message and each node receiving the update message for the first time will set the sender node as parent node. This process continues recursively until the packet reaches back to the base station. This approach will basically lead to a breadth first spanning tree with the base station as the root of the tree.

Tree based algorithms have been used in solving many computational complex problems. Using this structure the authors in [3] propose a secure cluster based multipath routing protocol (SCMR) for multimedia content. The multimedia application requires a better QoS and in order to achieve that, the nodes in the network have to process the data frequently and it causes faster depletion of energy at nodes. To achieve the data reliability and to provide a faster data computation, the protocol uses a hierarchical structure of multiple paths based on clusters. The multiple paths are discovered by message broadcasting and each cluster head node is connected to the sink either directly or via other cluster head node. The cluster head nodes are more powerful than the rest of the nodes in terms of available resources.

Benefiting from the tree structure the authors in [43] propose a failure recovery algorithm, MEEDMR for mission critical WSN application using multiple paths. The multiple paths and alternate paths are discovered by using tree based search algorithms from source to destination considering packet loss and packet delay. To provide reliable transmission, the data packets are distributed throughout multiple paths. Whenever the end-to-end reliability falls below a certain value, the route maintenance is performed. During the path maintenance additional paths have been added to the path set.

In a similar approach [46] G. Treplan *et. al.* propose a multipath routing algorithm (EERCM) which achieves data reliability by using a set of relay nodes. The relay nodes are selected based on their position in the hierarchy. For each transmission the set of selected relay nodes will be different. Furthermore the energy efficiency is achieved by avoiding the bottleneck nodes which have the capability to affect the network throughput and network lifetime [55]. Unlike relay nodes mentioned in the above protocol the proposed M2RC protocol in [32] decides the next hop based on the error condition of the downstream neighboring nodes. Each node has a local variable called branching factor (bfac) which observes the error condition of the neighboring nodes and keeps a count of them. During the path construction each node is assigned with a certain cost value which describes the power require to send the packet to the sink. The closer to the sink, the lesser will be the cost value. Whenever the source node transmits the message it attaches the cost value. The receiving node then compares its own cost with the cost value in the received packet and forwards the packet to the other neighboring node if it has a lower cost value or otherwise drop it.

In [50] the authors present a hierarchy-based multipath routing protocol (HMRP) which focuses on energy limitation in WSNs. The main objectives of this protocol are scalability, simplicity and extending system lifetime. In this work, multiple paths are constructed by broadcasting the message to neighboring nodes. Each receiving node forwards the message to their neighboring nodes and point them as their child node. This process continues until every node discovers its own children. In this architecture sink nodes act as root nodes. To make data transmission more reliable, each source node waits for acknowledgment from destination node before deleting the data from the buffer.

The above mentioned protocols propose prominent hierarchal approaches; however, there are still some problems. On one hand most algorithms, do not try to distribute the traffic to the whole network and do not take load balance into consideration. On the other hand, in the process of multipath construction, most heuristics such as energy level and others are not considered in the pursuit of an optimal path. In summary, hierarchy-based multipath routing provides a reliable mechanism to construct and maintain multiple paths in a resource constrained environment by constructing hierarchy and using existing techniques to maintain hierarchy. For example algorithms maintaining spanning tree can be applied in those protocols; however, they can be improved by integrating more heuristics and other techniques such as coding in the multipath protocol design.

5.1.3 Ant Based Algorithm

Ant based algorithm is another infrastructure based approach which is used to build multiple paths. The algorithm is a population-based metaheuristic approach inspired from behavior of real ants. The main idea behind this theory comes from observing the ability of ants to find the shortest path between the food source and the nest. Here is a breif example explaining the basics of this algorithm.

- An ant named 'xixi' roams independently in search of food.
- Once food is found, 'xixi' comes back directly to the nest leaving a trail of pheremones along the pathway.
- The rest of the ants follow the phermone trail and use the same path to get to the food.

On the basis of the working of the above algorithm two types of algorithms, AntNet algorithm and Ant-based control algorithm, have been developed [47].

In AntNet algorithm both forward ant and backward ant work together to grab the network information. The forward ants collect the node information and the backward ants utilize that information and update the routing table.

In [56] the authors use AntNet algorithm (MR-ACS) to find optimal paths from source to destination. In this approach the ants search for the path parallelly. This technique helps to find the paths quickly. The forward ants build the paths by applying metaheuristic approach to each intermediate nodes. If the intermediate node is already visited by another node then the forward ant will ignore it and move forward. If not, it will examine the closeness of the node to the sink and update the pheromone accordingly. The backward ants update the local pheromone on the basis of the information they have from the forward ants and find the optimum path.

In Ant-based control (ABC) algorithm the ants traverse the network based on the probability. Each node maintains a pheromone table for every possible destination. The ant will move from one node to another node based on the probability in the pheromone table.

In [59] J. Yang *et. al.* propose a multipath routing protocol (CACO) which is based on dynamic clustering and ant colony optimization algorithm. The algorithm is divided into three phases. In the initial phase a cluster head is selected based on the residual energy and signal strength. The cluster approach helps to prolong the network lifetime. In the next phase ant based approach is used to find the multiple paths between the cluster head and the sink node. In the final phase the cluster head selects the dynamic route to transmit the data.

By using the similar algorithmic approach the authors in [36] present a self-optimized algorithm using multipath routing (SOAMR). Once the shortest path is determined by the ant-based algorithmic approach, the routing decision will be made based on some forwarding metrics like packet receiving rate and remaining power of the neighboring node. This algorithm uses both multipath and single path routing to provide the best data throughput.

Ant based algorithm has many advantages in WSNs. Firstly, the underlying concept is really simple and it is a distributed approach in which multiple paths are discovered from all the possible areas. Hence, the traffic will be distributed evenly on the network which provides a better performance in terms of reliability and energy efficiency. Secondly, it is adaptive to any kind of network topology and even in system with a high dynamic environment this approach has a better successful rate. On the other side, the algorithm works really slow as compared to other heuristic approaches and in a high dynamic network the amount of overhead to find the shortest path is really high [18].

There are various other infrastructure based multipath routing protocols which use a hybrid approach by integrating several proposed protocols to design a more reliable and suitable protocol. For example in [9] the authors investigate the performance of two different multipath routing schemes, selective random forwarding (SRF) and selective preferential forwarding (SPF), and propose a hybrid protocol which contains the good features of both two schemes. In SRF scheme, the intermediate nodes decide the next hop based on the quality of other downstream neighboring nodes. In contrast, in the SPF scheme the multiple paths are discovered and then a predefined path is used to deliver the packet until it fails after which the next path will be used and so on. By integrating the salient features of both the schemes, the authors devise a novel protocol which is energy-efficient and reliable.

In another hybrid protocol [14] A. Eghbali and M. Dehghan propose an extended version of directed diffusion protocol called multipath directed diffusion (MPDD), which incorporates multipath routing with directed diffusion. The paper also discusses different methods and different routing schemes to find an efficient approach to handle the limited resources. The simulation result shows that multipath directed diffusion protocol provides a better performance in terms of energy efficiency and load distribution. Similar to the above paper the authors in [28] have done an extensive research on directed diffusion and proposed a new protocol (DCHT) which follows the basics of directed diffusion. The new protocol integrates multiple paths and path cost variable to maximize the throughput and improve the delay performance. During the data transmission each node considers the path cost metric to select the path with the lowest delay and better link quality. The path cost [27] is defined as:

$$PATH\_COST = PATH\_ETX^{\alpha} \times PATH\_DELAY^{\beta} \qquad (2)$$

$$PATH\_ETX = Max_{N-3}^{i=0}(\sum_{i+2}^{j=i} ETX_j) \quad (3)$$

Where N is the number of hops in the path, ETX is the Expected Transmission Count and α, β are non negative integers.

5.2 Non-Infrastructure Based Multipath Routing Protocols

Protocols which do not construct any infrastructure in order to transmit the data are considered non-infrastructure multipath routing protocols. The major difference between infrastructure based routing protocol and non-infrastructure based routing protocol is as follows. The path is discovered prior to the data transmission in infrastructure based routing protocol. On the the hand, in non-infrastructure based routing protocol, the path is discovered as the data packet moves forward. This means in non-infrastructure multipath routing, every intermediate data routing node makes a decision on the basis of its local knowledge instead of pre-set next hop information, in order to forward the packet. Because each node makes its own decision to forward the data packet, it is possible that instead of sending the data packet towards the sink node, the packet could be sent away from the sink node. Therefore, one of the major concerns of non-infrastructure multipath routing protocols is forwarding the data packet in the direction of the sink. This protects the packet from looping in the network which not only causes significant delay in the delivery of the packet, but also wastes a lot of energy.

Non-infrastructure multipath routing protocols also have many advantages. Firstly, their is no path maintenance required because as the packet moves forwards the path is created by the intermediate nodes based on their local knowledge. Secondly, the randomized routing mechanism, used by the protocols to route the data, is energy-efficient and helps to achieve load balancing. Finally, the protocols using dynamic packet state (DPS) in which each data packet header contains some information about network conditions from the previous node helps the receiving node make better forward decision. In WSN one of the special type of non-infrastructure based protocol is geography-based multipath routing protocol.

5.2.1 Geography-based Multipath Routing Protocols

Geography-based protocols take the location information of the nodes into consideration. In such protocols the routing decision is based on the position of the source node, neighboring nodes and the destination node. When an intermediate data routing node receives the data packet, it forwards the packet to the neighbor which is closest to the destination. Geography-based protocols have many advantages. Firstly, the nodes are not required to store the bulky neighboring tables. This saves the memory space and the energy used to construct those tables. Secondly, there is no path maintenance required because the path is constructed with the arrival of the data packet, on the basis of neighbor's location and destination location. Finally, by considering the location of the nodes, the query can be distributed only to a certain required region instead of the whole network, which can save a number of transmissions.

In summary, in geography-based multipath routing, each node knows the other nodes' position. The best next hop is selected on the basis of the nodes location and their distance to the destination node. These protocols are on-demand routing protocols, therefore paths are found only when required. The protocols belonging to this category are described as follows.

In [52] the authors propose a multipath routing algorithm (EECA) which focuses on designing collision free multiple paths. The authors assume that the network consists of N nodes, deployed statically in a two-dimensional region and each node has a transmission range R. The authors also assume that each node knows the location of the destination node. In order to transmit the packet toward the base station a route discovery message is broadcasted but only to the neighbors of the node. Each node transmits the route discovery message and data using a sufficient power level needed to reach the next hop, with the help of location information. This approach is more efficient and power conserving as compared to the flooding because the information is disseminated only to a specific portion of sensors, rather than to the whole network. When the source has a data packet to send, it first looks at its neighboring nodes and selects two groups of nodes satisfying the following three conditions. Firstly, all nodes are closer to the destination. Secondly, a group of nodes at one side of the source-destination line, should lie opposite to the other group of nodes. Finally, the distance between each node of the two different groups must be more than R/2 from the source-destination line.

The main reason behind selecting the nodes which are $R/2$ distance away from the source-destination line is to construct collision and interference free paths. If the two paths are apart by distance R, it guarantees that no collision will occur.

In [10] the authors propose a multipath routing approach, MMPRSF using meshed multipath routing. By using the meshed routes the nodes have multiple choices to forward the data packet. All the nodes in the network are static and the location information of each node is transmitted across the network using some mobile nodes during initial deployment. The meshed routes are discovered by query message. Once a node receives the query, it replies to the sender with a confirmation message. To avoid loops in meshed routes each node can receive a maximum of two queries and the first received query is forwarded to two downstream nodes. When the source node has data to forward, it uses selective forwarding, in which the routing decision is taken hop by hop depending on the condition of downstream nodes. The selective forwarding approach can distribute the packet to multiple paths, hence achieving load balancing. Intermediate data routing nodes are responsible for node failure or channel error.

The above protocols provide an efficient multipath routing approach by incorporating geography information; however, several issues need to be addressed as follows. Firstly, the geographic routing strategy has a major pitfall called the local maximum phenomena [31]. It occurs when a source node is not able to find any neighbor node closer to the destination than itself, due to the obstacle. In that case the source node drops the packet. Secondly, it is prone to malicious attacks. For example, sybil attacks can affect geography-based routing. In this type of routing, the nodes share the coordinate information to route the data. An adversary can pretend to be multiple nodes by providing faked coordinate information, which does not exist, but other nodes may not be able to tell whether it is a faked one or a real one. Whenever a source node selects such a faked node as an intermediate data routing node, the data can be lost.

Except for geography-based, non-infrastructure routing protocols can be built based on other heuristics. ReInForm is one of the good examples that uses a DPS mechanism to forward the data packet. The major focus of this scheme is to use the network resources efficiently, on the basis of the criticality of information and adaptability to channel errors. In ReInForM each data packet is assigned a priority level based on the content of the information it contains. The sink node periodically broadcasts a routing update packet, and each receiving node updates its neighbor list and the number of hops it is away from the sink. To achieve reliability the source sends multiple copies of the same data among multiple paths. The packet forwarding decision is taken locally by the source node using DPS mechanism. Moreover, to transmit the data in the direction of the sink, the neighbors of the source are divided into three subsets H_s^-, $H_s^0$and H_s^+. To find the number of paths required to transfer the data packet, the source node uses the following formula:

$$P(r_s, e_s, h_s) = \frac{log(1 - r_s)}{log(1 - (1 - e_s)^{h_s})} \tag{4}$$

Where P is the number of paths, r_s is the reliability based on the importance of the information, h_s is the hop distance to the sink and e_s is the local channel error.

Similar to ReInForM, [8] presents a novel multipath routing algorithm which increases reliability by using multiple paths and scheduling data transmission rate at each node. This approach helps to prevent congestion and packet loss. Each node in the network maintains two queues for incoming data and three queue for transmitting the data. Also, every packet is assigned a priority number based on the information it has. All the nodes in the network act as a scheduling unit and whenever any data arrives on the node, they put the packet in the appropriate queue. Later on, the node will select the packet based on the priority number from the queue and schedule a transmission to its next available multiple nodes. By using this approach the traffic on the network is controlled by adjusting the queue length.

The above mentioned protocol provides a high rate of reliability in the presence of channel errors; however, it does not provide a way to detect the failed nodes [12]

5.3 Coding Based Multipath Routing Protocols

This category consists of multipath routing protocols that use coding techniques in data transmission. In infrastructure based protocols, path construction and maintenance are two major overheads. Data transmission, however, will be straight forward by following the established routes, although in order to achieve reliability the same data packet is transferred through all multiple paths. This is energy inefficient and not secure. On the contrary, the non-infrastructure based protocols have no path construction and maintenance overheads, but have problems with secure data transmission and less likelihood of successful delivery on the sufficient number of paths. Therefore both the above categories have two common problems, unnecessary redundancy in transmission and security. Coding techniques can be used to address those two issues in multipath routing. Firstly, if some intermediate data routing nodes get into malicious activity, they will not be able to eavesdrop the network because the data packets travel in encoded form and are only decoded at the destination node. Secondly, it saves a lot of energy by not sending the same copy of data using multiple paths. Coding techniques compliment both infrastructure and non-infrastructure protocols discussed in Section 5.1 and Section 5.2, and they are mostly applied in the stage when data are transmitted from the source to the sink.

The protocols in this category split the data packet into fragments at the source node. After adding redundancy to fragments, they are transmitted to different discovered paths. At the destination node, in order to reconstruct the original data, the protocol requires a certain amount of fragments being received to successfully accomplish the decoding process. Therefore the other major concern of the protocols using coding technique is to determining the number of sufficient paths, because the number of fragments sent through a number of different discovered paths directly affects the decoding process at the destination node. There are different types of coding schemes such as erasure coding, network coding, and XOR- based coding, each of which has its own compression and decompression efficiency. The selection of the coding technique is based on the requirement of the application. Several representing coding based multipath routing protocols are discussed as follows.

In [54] the authors present a multipath routing approach using erasure coding (MREC). The protocol uses an on-demand routing algorithm in which a new path is constructed from source to destination only when it is required. This approach helps to conserve energy by not constructing unnecessary paths. In this protocol the multiple paths are constructed by broadcasting messages to the whole network. When the destination node receives the request message, it replies with a route reply message. To overcome redundant data transmission and data security issues, the protocol uses a data splitting technique called erasure coding. Erasure coding is a forward error correction (FEC) code in which the original data packet is split into k packets and redundancy of $n-k$ data packets are added to them. Finally these n sub packets are transferred through discovered multiple paths and on a destination node only k packets are necessary in order to recover the original data packet. In this way even if some of the data packets are lost for any reason, the original data can still be obtained. Along with that the amount of transmitted data will be very low because instead of transferring the whole data packet, the fragments of data packets will be transferred through different discovered multiple paths. Therefore, a lot of energy will be conserved in the transmission and the network lifetime will be prolonged.

In [13] [16] [15] the authors use the network coding in order to enhance the throughput, reliability, and robustness of the network. Network coding is a type of coding theory in which the data is encoded and transmitted at the source node. At an intermediate routing node, more data is added to the encoded packet by using the proper encoding coefficient to get maximum information from the network. The encoding coefficient ec is defined as ratio of n packets after network coding by k original packets at the source node, i.e.,

$$ec = n/k \tag{5}$$

In these protocols, the multiple paths are constructed by message broadcasting. The sink node periodically broadcast route update information and with the arrival of each route update message, the recipient node knows the distance between itself and the sink node. Whenever a source node has some data to send to the sink node, it determines the number of paths required to transfer the data based on channel quality and a Bernouli model. To select the next hop, the nodes in the network are divided into three sets, i.e., H^0, H^-, H^+. Nodes which have the same hops to the sink node from the source node consist of set H^0; nodes whose hops are smaller to the sink node are classified to set H^-, and the rest of nodes are belong to set H^+. Using this approach the data packet is always transferred in the direction of the sink because each set defines the distance between itself and the sink, and whenever a node has a data packet to transfer, it always looks for a node which lies in the set closer to the sink. The destination node, after receiving the required amount of data, decodes the packet using the encoding coefficient and the original data will be retrieved. In this approach the data will be secured in transmission and the decoding can only be done at the sink node.

Coding aware multipath routing protocol (CAMP) [19] is another multipath routing protocol which incorporates network coding to achieve data reliability and security. CAMP focuses on increasing the network throughput by switching the path dynamically based on the path reliability and better coding opportunity. The protocol works in two different phases. In the first phase the protocol constructs the multiple paths by message broadcasting. Whenever any node receives a route request from the neighboring node, it attaches Expected Transmission Count (ETX) of the previous link before transmitting it further. This technique helps both the destination node and the source node to have a global picture of the whole network. ETX is a measurement of the transmission link which is calculated based on the past events occurred on that link. In the second phase the packet is transmitted through multiple paths with the help of network coding. Whenever an intermediate node receives a packet, it will look for an alternate path which provides a better coding opportunity. This technique gives protocol a flexibility to choose any path based on its reliability and better transmission rate instead of following only pre-defined path.

In [58] the authors propose a robust and energy-efficient multipath routing protocol (REER). REER uses two different approaches for traffic allocation. In the first approach, it uses a single optimal path to transfer the data while the second approach uses multiple paths with XOR based error correction codes. The multiple paths are constructed by broadcasting a HELLO message through the network. Each node maintains a neighboring table which contains a list of capable nodes and on the basis of information contained in the neighboring table, the best next hop is selected. The selection of the best next hop is based on the link cost function, which is defined as:

$$NextHop = max_{yNx} \alpha E_{resd,y} + \beta B_{buffer,y} + \gamma I_{interference,(xy)} \tag{6}$$

Where $E_{resd,y}$ is the current residual energy of node y; $B_{buffer,y}$is the available buffer at node y, and $I_{interference,xy}$ is the link performance between node x and y, which is calculated in terms of signal-to-noise ratio (SNR). The total cost for a path P, which consists of a set of nodes K where the source node is x and the destination node is y, is calculated by.

$$C_{total,p} = \sum_{i=1}^{K-1} L_{(xy)_i} \tag{7}$$

Where $L_(x, y)$ is the sum of individual link cost.

In the working of REER-1 version of the protocol the source node will transfer the data to the destination over the best available path until its cost falls below a certain threshold value.

In the working of REER-2 version of the protocol the message is separated into N segments (S_0, S_1, S_{n-1}). On the head of $(M + 1)$ segments $(whereM < N)$ some error correction codes (C_0, C_1, C_2, C_m) are added to the original message. Then, the segments of the original message and their corresponding correction codes are sent to the destination node through the best available paths. At the destination, only N segments out of M+N segments are required in order to retrieve the original message.

In an another paper [11], the protocol constructs multiple paths and proposes a novel technique to extend the network lifetime. The protocol uses the same approach to construct the multiple paths and same coding technique to transmit the data as in REER but with an additional energy efficient technique. According to the authors, using two batteries in each node can significantly increase the battery life. By using two batteries, the power can be supplied from one battery for a certain amount of time and then switched to the other. This technique provides the other battery a chance to recover a portion of its lost power during the rest period.

The above protocols present effective multipath routing schemes incorporating the coding technique; however, there are still some concerns. With coding techniques, we need to pay attention to two issues in multipath protocol design. On one hand, simultaneous transmission of data from node disjoint paths may cause high data packet loss and affects the transmission performance [34]. On the other hand, failure in the consecutive nodes due to several obstacle can decrease the effectiveness of the coding scheme [26].

Protocol Name	LFT	LB	PDR	NoP	RST	TF	PLen	Delay
EEMR[30]	VG	GD	GD	Low	Mid	Low	Low	Low
M2RC[32]	VG	GD	GD	Low	Low	Low	Low	Low
QEMPR[21]	GD	GD	GD	Low	Mid	Low	Mid	Low
EEAMR [48]	VG	FR	GD	Low	Mid	Low	Low	Low
REEM[49]	FR	GD	GD	Low	High	Mid	Mid	Low
MRMS[7]	VG	GD	VG	Low	High	Low	Low	Low
EBMR[61]	FR	FR	FR	Low	Mid	Mid	Low	Low
N-to-1[29]	GD	FR	GD	Low	Mid	Low	Mid	Mid
SCMR[3]	GD	FR	GD	Low	Mid	Mid	Low	Low
MEEDMR[43]	PR	PR	FR	Low	Low	Low	Low	Low
SOAMR[36]	FR	FR	PR	VLow	Low	Low	Low	Low
MPDD[14]	FR	GD	VG	High	Mid	High	Mid	Mid
EERCM[46]	FR	GD	GD	Low	Low	High	Mid	Mid
HMRP[50]	FR	FR	FR	Low	Low	Mid	Low	Low
MR-ACS[56]	GD	PR	GD	Low	Low	Low	Mid	Mid
CACO[59]	GD	GD	FR	Low	Low	Low	Mid	Mid
EECA[52]	FR	FR	GD	Low	Mid	Low	Mid	Mid
MMPRSF[10]	VG	FR	GD	High	High	Low	Mid	Mid
ReInForM[8]	PR	FR	PR	Low	Mid	High	Mid	Mid
MREC[54]	FR	GD	GD	High	Mid	High	Low	Low
CAMP[19]	VG	GD	GD	High	Mid	Mid	Low	Low
REER[58]	VG	GD	GD	High	Mid	Low	Low	Low
DCHT[28]	PR	FR	FR	Mid	Low	Mid	Mid	Mid
HREEMR[16]	GD	GD	GD	High	Low	Low	Low	Low

Fig. 3 Qualitative comparison of the performance of above multipath routing protocols.

Having introduced different types of multipath routing protocols in previous sections, we summarize the performance of the reviewed multipath routing protocols in Figure 3. A total of 24 protocols are compared in Figure 3 in the context of the proposed performance metrics in Section 4. In the figure, VG means very good; GD means good; FR means fair; PR means poor and VLow means very low. In the figure, we can find that protocols using coding technologies usually have a better performance compared with those not using any coding technologies. The reliability is largely related with the number of paths but there are also other factors such as special fault-tolerant mechanisms that can also affect the reliability performance of the routing protocol. A lot of multipath routing protocols will not achieve the shortest path; while they mostly help to improve load balance which usually improves the performance of energy efficiency.

6 Related Work

Based on different requirements from various applications, routing protocol design usually has different performance focuses. Thus various routing protocols have been proposed with different motivations. Due to the importance of the routing protocol, there are a set of survey papers reviewing the routing techniques in WSNs from different perspectives. For example, in the literary, surveys on routing protocols from perspectives of real-time, security, dependability and fault-tolerance have been presented.

Surveys such as [1], [42], [2] present comprehensive reviews on previous routing protocols from all perspectives. In [1] the authors focus on discussing design challenges and design principles of various routing protocols in WSN. Moreover, advantages and disadvantages of each routing technique are analyzed. It incorporates multipath routing as one of its classifications but the description provided is very concise [1]. In [42] the authors present a comprehensive survey on various routing protocols and organize them on the basis of their characteristics including location-based, data-centric and so on. The paper also discusses protocol design and exhibits that the ultimate goal of a routing protocol is to be energy-efficient. Furthermore, the paper has an emphasis on 3D WSNs. Another paper [2] addresses various routing protocols with network architecture and their design issues. Routing protocols have been classified into three categories including data-centric, hierarchal, and location-based. In each category, appropriate examples are discussed. In addition, the paper presents some open problems and research issues related to the routing in WSNs. Our paper has a different focus. We provide a detailed study of multipath routing protocols.

One set of surveys on reliable, dependable, fault-tolerant routing protocols are the most closest ones to our work. In [22] the authors discuss the fault-tolerant technique of routing protocols in WSNs. According to the paper, multipath routing is the best approach for fault-tolerance. In Hind and Agarwal's work [22], fault-tolerant routing protocols are classified into two classes, retransmission based and replication based. The performance of those protocols is analyzed on the basis of performance metrics including energy consumption, memory usage and so on. In another paper [24] the authors present the concept of routing dependability in various networks, which is defined as trustworthiness of the routing scheme and its performance. According to the paper the success of sensor network depends on the co-ordination between the nodes and the area where they are deployed. In [35] the authors present a survey on routing protocols and discuss the problem of end-to-end reliability. The paper discusses various transport protocols and includes a detailed comparison of their functionality. Comparing to the above survey papers, our paper is focused on multipath routing. We presented a set of multipath routing protocols and classified them on the basis of their routing techniques. Moreover, we also present the challenges and advantages of multipath routing in WSNs. In order to analyze the performance of multipath routing protocols, some performance metrics are discussed as well. To the best of our knowledge, this is the first survey which is devoted to the multipath routing protocols.

There are also surveys of routing protocols in WSNs which focus on a special protocol design goal. For example, security routing protocols, in which the major goal is to design a routing protocol that prevents or tolerates malicious attacks, are surveyed in [44]. Based on different security design goals, routing protocols are classified into different categories including multipath routing protection, attack-specific, and security operations support. Furthermore, the protocols are evaluated on the basis of fundamental evaluation metrics in WSNs such as energy consumption, communication overhead and so on. [45] presents a survey on new model of routing based on Distributed Hash Tables (DHT). In that paper, the detailed design of routing protocols based on DHT are discussed and the performance of those protocols are compared in terms of scalability, energy-efficiency, and data storage efficiency. Real-time is an important component of a lot of WSN applications, thus real-time routing protocols are reviewed in [62], which focuses on time-critical issues. The paper provides classification of the real-time routing protocol in different categories including hierarchical architecture, location-based, scalability, energy efficiency and link reliability. The paper concludes with some open issues and suggestions for future research. The survey papers discussed above are helpful for the researchers in correlating fields; however, our survey is different in that we present a comprehensive survey on multipath routing protocols.

7 Conclusion

In this paper, we take an initial step to overview the proposed multipath routing protocols in WSNs. We classify multipath routing protocols mainly based on whether the proposed routing protocol creates multiple path infrastructure or not. Furthermore, because of the special importance of coding techniques in multipath routing, we discuss a set of coding technique based multipath routing protocols in detail. In addition, a group of multipath routing protocol design issues such as major design goals, challenges and evaluation metrics are presented in the paper.

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