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Multipath Routing in Wireless Sensor Networks: A Survey and Analysis

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Abstract: *Due to restricted communication range and high density of sensor nodes in wireless sensor network, forwarding packets is an important field of research in sensor networks. Nowadays, multipath routing approach is widely used in wireless sensor networks to improve network performance through efficient utilization of the available network resources. The main aim of this survey is to present the concept of multipath routing, as well as the basic motivations for utilizing this technique. In addition, this paper presents a comprehensive taxonomy on the existing multipath routing protocols. This paper also highlights the objective behind the development of each protocol category. Finally, a detailed study has been made on the design and operation of the different protocols, with emphasis on their advantages and disadvantages.*
Keywords: *Wireless sensor networks; alternate path routing; concurrent multipath routing; reliability; path discovery.*

I. Introduction

Recent advances in wireless communication technology have led to the introduction of low-power wireless sensor networks. Due to ease of deployment and multi-functionality of sensor nodes, wireless sensor networks have been adopted by many fields as a promising solution to numerous challenges. For example WSN is used in a variety of applications such as target tracking, healthcare and environmental monitoring [1]. Unreliability of low-power wireless links and resource limitations of sensor nodes imposes challenges in design of efficient communication protocol for wireless sensor networks [2]. In order meet different performance demands of various applications, designing suitable routing protocols is an important issue in sensor network.

Most of the existing routing protocols in wireless sensor networks are designed based on single path routing strategy without considering the effect of various traffic load intensities. In this approach, each sensor nodes sends its data to the sink node via the shortest path. Although route discovery through single-path routing approach can be performed with minimum resource utilization and computational complexity, limited capacity reduces the achievable network throughput [3,4]. Furthermore, the node and link failure may also considerably reduce the network performance in critical situations. In order to cope up with the limitations of single-path routing strategy, another type of routing strategy called the multipath routing has become a promising technique in wireless sensor networks. Multipath routing is an alternate routing technique which selects multiple paths to deliver data from source to destination. Due to multipath routing increase in the number of possible routes increases the robustness and throughput of the transmissions. Multipath routing is used either for load balancing or for reliability. Load balancing can be achieved by balancing the energy utilization across the nodes of the network, resulting in enhanced network lifetime.

II. Multipath Routing In Wireless Sensor Network

Multipath routing approach is utilized as one of the possible solution to cope with the limitation of single-path routing approach. This section presents the motivation behind using multipath routing approach and also discusses the main design issues in the development of multipath routing protocols.

1.1. Motivations for Using Multipath Routing Approach in Wireless Sensor Networks

Data Reliability: Reliable data transmission in wireless sensor networks is a challenging task. Multipath routing approach provides resilience to node or link failure and reliable data transmission. There are two different approaches to provide reliable data delivery through multipath routing. The first approach is achieved by sending multiple copies of the same data on multiple paths to ensure packet recovery from path failures. Another technique used by some of the existing protocols is erasure coding to provide reliability. In this coding technique, each source node adds some additional information to the original data packets and then distributes generated data packets over different paths. Therefore, in order to reconstruct the original packets, a certain number of data packets from each source node should be received by the sink node. Even if the delivery of some data packets to the sink node fails, still ensures reliability by reconstructing data packets from successfully received data packets by the sink node.

Improving Fault Tolerance: WSNs are often subject to high failure rates due to environmental noise and obstacles, environmental changes, and nodes may die due to battery depletion. In such an environment, reliable and energy-efficient data delivery is crucial as sensor nodes are often operated with limited battery power on error-prone wireless channels. The path breaks due to node failure leads to the requirement of additional routing overhead in order to find alternative paths, which results in energy consumption of the nodes and affects the network lifetime. So the routing protocols must be designed to achieve fault tolerance in the presence of individual node failure thus keeping energy consumption at a minimum. Multipath routing protocols can provide fault tolerance by having redundant information routed to the destination via alternative paths. Thus in case of link failure it reduces the probability that the communication is disrupted.

Load Balancing: The main aim of load balancing is to make use of available network resources in order to reduce network congestion. Intensive traffic load in high-data rate applications causes congestion, which influences network performance [5,6]. For this purpose, multipath routing approach can provide best solution through splitting the network traffic over several paths and thus reducing the probability of network congestion. Multipath routing approach also prolongs network lifetime by distributing the network traffic over sensor nodes resulting in even energy distribution among the nodes.

Bandwidth Aggregation: By splitting data into multiple streams to the same destination, each routed via a different path, effective bandwidth can be aggregated. This approach is particularly beneficial when a node has multiple low bandwidth links but it requires bandwidth that is greater than the one which an individual link can provide [7].

QoS Improvement: QoS support in terms of network throughput, data delivery ratio and end-to-end latency is an important objective in the design of multipath routing protocols for different types of networks [8,13]. Based on the QoS demands of the application for which the multipath routing protocol has been designed, discovered paths with various characteristics can be utilized to distribute network traffic. For example, the time critical data packets can be transmitted through higher capacity paths with minimum delay while on the other hand the delay insensitive non-critical data packets can be transmitted through non-optimal paths with higher end-to-end delay. Multipath routing approach can preserve QoS demands of the intended application in the case of path failures through directing network traffic to another active path.

1.2. Basic Elements in Designing Multipath Routing Protocols

Each multipath routing protocol includes several components to construct multiple paths and distribute traffic over discovered paths. These components are described below.

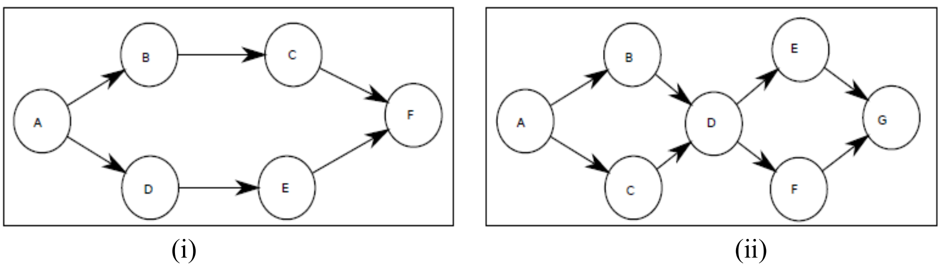
Path Discovery: As the data transmission in wireless sensor networks is commonly performed through multi-hop data forwarding techniques, the main aim of route discovery process is to determine a set of intermediate nodes that should be selected in order to construct several paths from source to sink nodes. Different parameters are used to make routing decisions and among these the main parameter which is utilized is the amount of path disjointedness to discover several paths from each sensor node to the sink node [8,12]. Fig. 1 depicts the discovered paths that can generally be categorized as node-disjoint, link-disjoint or partially disjoint paths.

i. Node-Disjoint Multipath: Refers to set of paths in which there is no common node among the discovered paths. Therefore, they are unaffected by node failure on the other paths. Node-disjointedness provides higher aggregated network resources. But due to random deployment of sensor nodes, it's difficult to find large set of node-disjoint paths between sensor nodes and sink nodes.

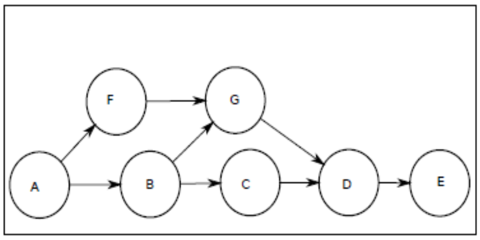
ii. Link-Disjoint Multipath: Refers to set of paths in which there is no shared link between the paths but may share some common intermediate nodes. Node failure in a set of link-disjoint paths may affect several paths that shared the failed node.

iii. Partially-Disjoint Multipath: Refers to set of paths which may share several links or nodes between different paths. Any link or node failure in a set of partially-disjoint paths may deactivate several paths. Still constructing multiple partially disjoint paths can be easily performed.

iv.



(i) (ii)



(iii)

Fig. 1 Various types of path disjointedness (i) Node-Disjoint Paths, (ii) Link-Disjoint Paths and (iii) Partially-Disjoint Paths

Path Selection and Traffic Distribution: After discovering multiple paths, another issue that needs to be addressed is the number of paths that should be selected for data transmission. Therefore, in order to meet the performance demands of the intended application, proposing a path selection mechanism to choose a certain number of paths is an important part of designing high-performance multipath routing protocol. After selection of set of paths among the discovered paths, multipath routing protocol should now determine how to distribute the traffic over selected paths. Various traffic allocation mechanisms are utilized to distribute the data amongst the selected paths.

Path Maintenance: In multipath routing, usage of multiple paths from source nodes to the sink nodes needs to be maintained periodically in order to achieve reliable data delivery. If the path is broken, then the sensor nodes have to select another optimal path. Thus path reconstruction should be provided to reduce performance degradation. Path rediscovery process is initiated in three different situations:

i. When an active path fails
ii. When a certain number of active paths have failed
iii. When all the active paths have failed

Performing a route discovery process after the failure of an active node imposes high overhead. Initiating a route discovery process after the failure of all the active paths significantly reduces the network performance. Thus initiating a route discovery process after a certain number of active paths have failed may present a trade-off between the advantage and disadvantage of the first two approaches.

III. Taxonomy Of Multipath Routing Protocols

The three main classes of multipath routing approaches based on the employed path selection and traffic distribution mechanisms.

1.1. Alternate Path Routing

As link and node failures are the main causes of path failures, the primary objective of developing multipath routing protocols is to provide fault tolerance. Discovering and maintaining multiple paths improves network performance by providing alternate paths. Whenever the primary path fails, alternate path transfers the data; while the multiple paths are not used simultaneously [9]. Table 1 summarizes few of the protocols from this category.

Directed Diffusion [10] is a query-based routing protocol to provide path failure protection. Routing operation is initialized by sink node through flooding interest messages throughout the network. Upon reception of an interest message, receiving node creates a gradient towards the node from which this message has been received. Whenever a source node detects an event matched with the existing information in its interest table, the data packets are transmitted towards the sink node through all the constructed gradients.

Braided Multipath Routing Protocol [14] utilizes two types of path reinforcement messages to construct partially disjoint paths. Path discovery is initiated by sending primary path reinforcement message by the sink node to its best neighboring node towards the source node. When an intermediate node receives a primary path reinforcement message, this message is forwarded to its best next-hop neighboring node. This process continues until the primary path reinforcement message reaches the source node. The sink and intermediate nodes also generate an alternative path reinforcement message and send this message to their next preferred neighboring node towards the source node. This process terminates upon reception of this message by one of the nodes along the primary path. Whenever the primary path fails to forward data packets towards the sink node, any one of the established alternative paths can be utilized to provide reliable data transmission.

Reliable Energy Aware Routing Protocol [11] protocol provides reliable data transmission through maintaining a backup path from each sensor nodes towards the sink node. Whenever interest message is received by the sink node from a source node, it initiates a service-path discovery process through flooding a service-path request message. On the service-path request message reception, the receiver node transmits a service-path reservation message towards the sink node to confirm the established path. While the service-path reservation message moves from the source node towards the sink node, if any node along the reverse path receives this message, that node then reserves a part of its residual battery level for data transmission over this path. This process of service-path construction finishes by receiving the service-path reservation message at the sink node and the source node can transmit its data packets towards the sink node through the constructed path. Sink node also initiates another path discovery process to establish a backup path towards the same source node by flooding a backup path discovery message. The intermediate nodes which are not a member of the established service-path, broadcast the received backup path discovery message received to its neighbors. Therefore, a node-disjoint path is created to provide fault tolerance in the case of path failure.

1.2. Concurrent Multipath Routing

Multipath routing approach improves reliability through concurrent data forwarding over multiple paths.

1.2.1. Multipath Routing Protocol for Reliable Data Transmission: Multiple paths can be used simultaneously to cope with the resource limitations of low-cost sensor nodes. As long as one of the multiple paths does not fail, receiver node receives the data. The probability of data delivery increases through introducing data redundancy during the data transmission process. Table 1 summarizes few of the protocols from this category.

N-to-1 Multipath Routing Protocol [15] is proposed to simultaneously discover multiple node-disjoint paths from all the sensor nodes towards a single sink node. During data transmission phase, intermediate nodes utilize a packet salvaging technique at each hop to improve reliability. In N-to-1 multipath routing protocol, routing operation is performed through a simple flooding strategy in two stages. Route discovery process is initiated by sink node at the first stage through broadcasting a route update message to construct a spanning tree and discover several paths from sensor nodes towards a single sink node. Each sensor node that receives a route update message for the first time, the sender of this message is selected as the parent. This process continues until all the sensor nodes discover their primary path towards the sink node and a spanning tree is constructed through all nodes. The second stage is initialized in order to discover more paths from each sensor node towards the sink node with the use of multipath extension flooding technique. Each link between two individual nodes that belong to different branches of the constructed spanning tree can help to establish an additional path from these nodes towards the sink node. Finally, source node splits the traffic into several segments and transmits these data segments over the discovered paths.

H-SPREAD [16] protocol utilizes the N-to-1 multipath routing algorithm to construct multiple paths with a hybrid data transmission technique to improve reliability and security of data transmission. Through threshold secret sharing scheme, the packets can be safely forwarded towards the sink node even when a certain number of paths have failed due to link or node failures during the data transmission process. The source node divides each data packet to the multiple shares, using the secret sharing strategy and then transmits them towards the sink node through different paths. The original message can still be retrieved via other received shares at the destination node. H-SPREAD only improves reliability and security of data delivery in the network.

Multipath Multispeed Protocol (MMSPEED) [22] is an extension of the SPEED protocol. MMSPEED is characterized by offering multi-speed transmission and establishment of more than one path to the destination to guarantee timeliness packet delivery. For each offered speed, a QoS level and an additional path can be set to improve the quality of traffic. This protocol allows sending packets with respect to end delay parameter required by applications in order to avoid congestion and reduce the packet loss rate. MMSPEED provides reliability differentiation through controlling number of active paths and sending multiple copies of the original data packets over several paths. Each intermediate node selects a set of next-hop neighboring nodes towards the destination node based on the estimated packet loss rate over each link and their geographic distance from itself. This protocol is adaptable and scalable to large networks. The only limitation of the MMSPEED is that the energy metric is not taken into consideration [18].

Multi-Constrained QoS Multipath Routing (MCMP) [20] protocol that uses set of partially disjoint routes to deliver packets to the sink node in order to satisfy QoS requirements in terms of reliability and delay. During the route discovery process, all the intermediate nodes choose the neighboring node that fulfills the delay requirement of the intended application. Each node selects one or a set of its neighboring nodes towards the sink node to provide reliability. Therefore, at the end of the route discovery process, each source node discovers a set of partially disjoint routes that can additively satisfy delay and reliability demands of the target application. The maximum achievable data transmission rate is highly affected using this protocol since partially disjoint paths are usually located nearby, causing significant interference at high data rate transmission.

Energy Constrained Multipath Routing (ECMP) [19] extends the MCMP to provide energy-efficient communication, while at the same time it also satisfies the delay and reliability requirements. ECMP introduces an energy optimization problem. Energy optimization problem is constrained by reliability, delay and geospatial energy consumption to provide multi-constrained QoS routing in sensor networks. Thus, ECMP supports multi-constrained QoS routing with minimum energy consumption.

Delay-Constrained High-Throughput Protocol for Multipath Transmission (DCHT) [17] is the modified version of Directed Diffusion that uses multipath routing approach to support high-quality video streaming in low-power wireless sensor networks. The protocol introduces a novel path reinforcement method and uses a new routing cost function that takes into account the expected transmission count (ETX) [21] and delay metrics to discover high-quality paths with minimum end-to end delay. The utilized path reinforcement strategy and routing metric in DCHT greatly improves the performance of the original Directed Diffusion by constructing multiple low-latency high-quality paths.

Energy-Efficient and QoS-based Multipath Routing Protocol (EQSR) [23] is designed to satisfy the reliability and delay requirements of real-time applications. EQSR maximizes the network lifetime through balanced energy consumption across multiple nodes. It improves reliability using a lightweight XOR-based Forward Error Correction (FEC) mechanism, which introduces data redundancy. In order to fulfill the delay requirements of various applications, this protocol utilizes the concept of service differentiation to allow high important traffic to reach the sink node within an acceptable delay. EQSR uses Signal-to-Noise Ratio (SNR), residual energy and node available buffer size to predict the best next hop during the path construction phase [28].

Reliable Information Forwarding (ReInForm) Using Multiple Paths in Sensor Networks [25] uses packet duplication technique to provide data transmission reliability. Whenever a source node wants to forward its traffic towards the sink node, source node firstly determines the required data transmission reliability. After that, the source node adds some information as Dynamic Packet State (DPS) fields to the data packets and transmits multiple copies of the generated data packets over several routes. The source node determines the required number of routes to fulfill the reliability demands of the collected information according to the DPS fields of the data packets. All the intermediate nodes determine the number of copies that should be transmitted to their next-hop neighboring nodes. Until all the transmitted data packets reach to the sink node this process continues. ReInForm protocol tries to improve data transmission reliability at the high cost of energy consumption and bandwidth utilization in resource-constrained sensor nodes.

1.2.2. Multipath Routing Protocols for Efficient Network Resource Utilization: The key idea behind the development of this protocol is to balance network traffic and resource utilization throughout the network. Table 1 summarizes few of the routing protocols from this category.

Energy-Efficient Multipath Routing Protocol [27] distributes the network traffic over the multiple node-disjoint paths. Whenever an event occurs, a sensor node in the event area is selected as the source node. The selected source node initiates the route discovery process and transmits multiple Route-request messages to its neighboring nodes. Route-request messages include different path IDs to construct multiple node-disjoint paths from the selected source node towards the sink node. All the intermediate nodes select one of their best next-hop neighboring nodes that are not included in any other paths during the route discovery process. Sink node upon reception of the first Route-request message, sets its timer to fulfill the path establishment process in an acceptable period. All the paths discovered after the timer timeouts are considered as low-quality paths and the Route-request messages received from these paths are discarded by the sink node. Then, the sink node assigns different data rates to the established paths. The main objective of this protocol is to prolong network lifetime by distributing network traffic over several paths according to cost of data transmission over these selected path.

AOMDV-Inspired Multipath Routing Protocol [24] is designed to achieve energy-efficient and low-latency communication through using cross-layer information in wireless sensor networks. Path construction in AOMDV-Inspired Multipath Routing Protocol uses different routing table management strategy to construct only hop count optimal paths towards the destination node. The sink node confirms an additional path only if its first hop is different from the previously established paths and if this path provides the same hop count towards the sink node. However, if the sink node receives a Route-request message with lower hop count than the existing routes, it substitutes all the previously established paths by the newly discovered path. AOMDV Inspired Multipath Routing Protocol utilizes the information provided by the MAC layer to reduce data transmission latency. Each intermediate node during data transmission process searches its routing table and forwards its received data packets to the next-hop neighboring node that wakes up earlier. Though this MAC layer technique can reduce the interference and transmission delay, it requires all the sensor nodes to be aware of their neighboring nodes timing information. This protocol requires flooding the whole path information throughout the network during the route discovery phase which imposes significant overhead to the already resource-constrained sensor nodes.

Maximally Radio-Disjoint Multipath Routing (MR2) [29] satisfies bandwidth requirements of multimedia applications through an adaptive incremental technique to construct minimum-interfering paths. Additional paths are constructed whenever the active paths fail to fulfill the bandwidth requirements of the available network traffic. The sink node initializes the route discovery process by flooding the network with a request message. Upon reception of the request message, the receiver node adds its ID to the received request message as the path ID and rebroadcasts this message. Thus, whenever a node receives a request message, it first checks the path ID and if it has not any path from the source node to the sink node, it should add the reported path to its routing table. However, if the path ID in the received request message already exists in the routing table of the receiver, the reported path should be replaced with the previous one if it provides a path with lower hop count. An update operation on the routing table, the receiver node should rebroadcast the request message. This process continues until the request message is received by a sensor node that can provide sink node with the requested data. Finally, source node starts packet transmission towards the sink node through the shortest discovered path. To address the mutual interference problem, all the intermediate nodes along the active path should notify their neighboring nodes to act as the passive nodes. The passive nodes can be put in sleep or idle modes, thus saving energy and hence increasing the network lifetime [26].

Energy-Efficient and Collision-Aware Multipath Routing Protocol (EECA) [30] uses the location information to establish two collision-free paths between a pair of source-sink nodes. Furthermore, the distance between these two discovered routes is more than the interference range of the sensor nodes. During the first stage of the route discovery, the source node checks its neighboring nodes to find two distinct groups of the nodes on both sides of the direct line between the source-destination pair. Thereafter, the source node broadcasts a Route-request packet towards these nodes to establish two node-disjoint paths. Each intermediate node during the route discovery process utilizes the same strategy to select their next-hop neighboring nodes and broadcast the received Route-request packet towards the sink node. The receiver node uses a back-off timer to restrict the overhead introduced by the route discovery. The intermediate nodes before broadcasting the received Route-request packet set a back-off timer according to their distance from the sink node and their residual battery level. Therefore, at each stage of flooding only one node wins to broadcast its received Route-request packet towards the sink node. Sink node upon reception of the Route-request packet sends a Route-reply packet towards the source node. Whenever the source node receives a Route-reply packet, it transmits its traffic through the established path.

Low-Interference Energy-Efficient Multipath Routing Protocol (LIEMRO) [31,32] discovers multiple interference-minimized node-disjoint paths between source node and sink node. Whenever an event occurs the selected source node starts to establish the first path by transmitting a Route-request message towards the sink node. Source node and all the intermediate nodes select one of their next-hop neighboring nodes. Sink node upon reception of the first Route-request message sends a Route_reply message towards the source node. Whenever a node overhears this message it updates its interference level value based on the backward packet reception probability of the node from which it overhears this message. Upon reception of a Route_reply packet by the source node, it transmits its data packets through the established path and starts the construction of another path by sending a new Route-request message towards the sink node. Path discovery process continues in an iterative manner as long as the new path results in higher end-to-end throughput. If the last established path reduces the end-to-end throughput, sink node asks the source node to disable the last constructed path. Upon establishing a new path, the source node transmits a portion of its traffic through this path using load balancing algorithm which calculates the optimal traffic rate of the established paths based on their accumulated residual battery level, interference level experienced and the probability of successful forward and backward packet reception.

Table I

Protocols	Path Disjointedness	Energy-Efficient	Delay	Fault-Tolerance	Reliability	QoS
Directed Diffusion	Node-disjoint	Yes	No	Yes	No	No
REAR	Node-disjoint	Yes	No	No	Yes	No
N-to-1	Node-disjoint	No	No	No	Yes	No
H-SPREAD	Node-disjoint	No	No	No	Yes	No
MMSPEED	Partially disjoint	No	Yes	No	Yes	Yes
MCMP	Partially disjoint	No	Yes	No	Yes	Yes
ECMP	Partially disjoint	Yes	Yes	No	Yes	Yes
DCHT	Node-disjoint	No	Yes	No	Yes	Yes
EQSR	Node-disjoint	Yes	Yes	Yes	No	Yes
ReInForm	Link-disjoint	No	No	No	Yes	No
Energy-Efficient Multipath Routing Protocol	Node-disjoint	Yes	No	No	Yes	Yes
EECA	Node-disjoint	Yes	Yes	Yes	Yes	Yes
LIEMRO	Node-disjoint	Yes	No	Yes	Yes	Yes

IV. Conclusion

Multipath routing is considered as an efficient method to improve network capacity and resource utilization under heavy traffic conditions. With recent advances in the development of multipath routing protocol, there is a need to investigate the detailed operation and classification of the proposed approaches. This paper presents a comprehensive analysis of the multipath routing protocols for wireless sensor networks. This paper highlights the main advantages of using multipath routing to meet performance requirements of different applications. Furthermore, this paper also introduces a new taxonomy on the multipath routing protocols designed for wireless sensor networks.

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