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MULTIPATH ROUTING IN WIRELESS SENSOR NETWORKS: A SURVEY AND ENERGY CONSUMPTION ANALYSIS

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Abstract: A Wireless Sensor Network (WSN) is group of spatially dispersed and dedicated sensors for monitoring and recording the physical conditions of the environment and organizing the collected data at a central location. Wireless sensor networks are deployed in an unattended environment in which energy replenishment is very difficult. Due to the restricted communication range and high density of sensor nodes, packet forwarding in sensor networks is usually performed through multi-hop data transmission. Therefore, routing in wireless sensor networks has been considered an important field of research over the past decade. Nowadays, multipath routing approach is widely used in wireless sensor networks to improve network performance through efficient utilization of available network resources. Accordingly, the main aim of this survey is to present the concept of the multipath routing approach and its fundamental challenges, as well as the basic motivations for utilizing this technique in wireless sensor networks. In addition to this, an energy consumption analysis of various multipath routing protocols is performed.
Keywords: Wireless sensor network; Multipath routing; Quality of service (QOS); Reliability; Energy Efficiency.

I. INTRODUCTION

Recent advances in wireless communication technologies and the manufacture of inexpensive wireless devices have led to the introduction of low-power Wireless sensor networks (WSNs). Due to their ease of deployment and the multi-functionality of the sensor nodes, wireless sensor networks have been utilized for a variety of applications such as war fields, emergency rescue operations and environment monitoring. The main responsibility of the sensor nodes in each application is to sense the target area and transmit their collected information to the sink node for further operations. Resource limitations of the sensor nodes and unreliability of low-power wireless links, in combination with various performance demands of different applications impose many challenges in designing efficient communication protocols for wireless sensor networks. Most of the existing routing protocols in wireless sensor networks are designed based on the single-path routing strategy without considering the effects of various traffic load intensities. Although route discovery through single-path routing approach can be performed with minimum computational complexity and resource utilization, the limited capacity of a single path highly reduces the achievable network throughput. Furthermore, the low flexibility of this approach against node or link failures may significantly reduce the network performance in critical situations. In order to cope with the limitations of single-path routing techniques, another type of routing strategy, which is called the multipath routing approach has become a promising technique in wireless sensor networks. Dense deployment of the sensor nodes enables a multipath routing approach to construct several paths from individual sensor nodes towards the destination. Discovered paths can be utilized concurrently to provide adequate network resources in intensive traffic conditions. Multipath routing approach has been widely utilized for different network management purposes such as improving data transmission reliability, providing fault-tolerant routing, congestion control and Quality of Service (QOS) support in traditional wired and wireless networks. Existing multipath routing protocols proposed for traditional wireless networks cannot be used directly in low-power sensor networks. During the past years, this issue has motivated the research community of wireless sensor networks to develop multipath routing protocols which are suitable for sensor networks. There are several papers surveying proposed routing protocols for wireless sensor networks. These surveys describe and analyze the general routing strategies proposed for wireless sensor networks. These literatures have presented routing challenges and design issues in wireless sensor networks. They classified all the existing routing strategies based on the network structure and protocol operation. Accordingly, the principal motivation of conducting this research was lack of a comprehensive survey on the energy efficiency of proposed multipath routing protocols for wireless sensor networks. This paper provides a deep analysis on the most recently proposed multipath routing protocols, highlighting their advantages and disadvantages.

II. ROUTING IN WSNs

As data transmission from the target area towards the sink node is the main task of wireless sensor networks, the utilized method to forward data packets between each pair of source-sink nodes is an important issue that should be addressed in developing these networks. Due to the intrinsic features of low-power wireless sensor networks, routing in these networks is much more challenging compared to the traditional wireless networks. First of all, according to the high density of sensor nodes, routing protocols should be able to support data transmission over long distances, regardless of the network size. In addition, some of the active nodes may fail during network operation due to energy depletion of the sensor nodes, hardware breakdowns or environmental factors, but this issue should not interrupt the normal network operation. Moreover, as sensor nodes are tightly limited in terms of power supply, processing capability, memory capacity and available bandwidth, routing and data dissemination should be performed with efficient network resource utilization. Furthermore, since the performance demands of the wireless sensor networks are application specific, routing protocols should be able to satisfy the QOS demands of the application for which the network is being deployed. For example, challenges in designing routing protocols for time critical applications are different from issues that should be considered in developing routing protocols for applications such as habitat monitoring.

The existing routing protocols in wireless sensor networks can be classified from two different perspectives: (1) network structure and (2) protocol operation. From the network structure point of view, routing algorithms are classified as flat, hierarchical and location-based routing protocols. Flat routing protocols are designed for networks with homogenous nodes, i.e. all the network nodes have the same processing and data transmission capabilities while their packet forwarding role is also similar. Hierarchical routing protocols were proposed to improve network scalability and energy efficiency through node clustering. In this group of routing protocols, all the sensor nodes are grouped into clusters and one node with more resources in each cluster is assigned as the cluster head. Each cluster head is responsible for processing the received data packets from its cluster nodes, communicating with other cluster heads or the sink node, and coordinating the cluster nodes. In contrast, all the cluster members should sense the environment and forward their collected data towards the respective cluster head for further operations. Although this approach can provide higher network scalability, clustering operation and cluster head replacement impose high signaling overhead to the network. Routing protocols in the last group utilize the exact location of the sensor nodes to make routing decisions. The geographic locations of sensor nodes can be obtained directly using Global Positioning System (GPS) devices or indirectly by exchanging some information regarding to the signal strengths received at each node. However, since localization support requires specific hardware components and imposes significant computational overhead to the sensor nodes, this approach cannot be easily used in resource-constrained wireless sensor networks. In contrast with single-path routing techniques, multipath routing protocols allow each source node to find multiple paths towards the sink node to improve network performance. Since, in wireless sensor networks, all the network nodes cooperatively process the flooded data in the network, the last group of routing algorithms is dedicated to the coherent data processing-based routing protocols. In this group, data packets are sent to the aggregators in order to reduce data redundancy. Therefore, energy efficiency is the main purpose of these routing protocols.

III. MULTIPATH ROUTING IN WSNs

The limited capacity of a multi-hop path and the high dynamics of wireless links, single-path routing approaches are unable to provide efficient high data rate transmission in wireless sensor networks. Nowadays, multipath routing approach is broadly utilized as one of the possible solutions to cope with this limitation. The main design issues in the development of the existing multipath routing protocols are discussed below.

A. Reasons for opting Multipath routing in Wireless Sensor Networks

Routing technique has demonstrated its efficiency to improve wireless sensor networks' performance. In the following, the performance gains that can be achieved using multipath routing approaches are discussed.

1) Reliability and Fault-Tolerance:

The time-varying characteristics of low-power wireless links, dynamic network topology, and wireless interference, make reliable data transmission in wireless networks a challenging task. The idea behind using multipath routing approach in wireless sensor networks is to provide reliable data transmission. In the fault tolerance domain, whenever a sensor node cannot forward its data packets towards the sink, it can benefit from the availability of alternative paths to salvage its data packets from node or link failures. Through this mechanism, as long as an alternative path is available from a target area towards the sink node, data forwarding can be continued without any interruption even in the case of path failure. Multiple paths also can be used simultaneously to elevate data transmission reliability.

2) Load Balancing and Bandwidth Aggregation:

Intensive traffic loads in high-data rate applications are prone to congestion, which highly influences the network performance. To handle this problem, data dissemination algorithms can profit from the high density of wireless sensor networks to increase network capacity by employing more network resources. For this purpose, multipath routing approaches can provide the best solution to support the bandwidth requirements of different applications and reduce the probability of network congestion through splitting network traffic over several paths.

3) QOS Improvement:

QOS support in terms of network throughput, end-to-end latency and data delivery ratio is an important objective in designing multipath routing protocols for different types of networks. Discovered paths with various characteristics can be utilized to distribute network traffic based on the QOS demands of the application for which the multipath routing protocol has been designed. For instance, time critical data packets can be transmitted through higher capacity paths with minimum delay while delay insensitive non-critical data packets can be forwarded through non-optimal paths with higher end-to-end delay. Furthermore, in contrast with the single-path routing techniques multipath routing approaches can preserve QOS demands of the intended application in the case of path failures through directing network traffic to the another active path.

IV. SURVEY ON MULTIPATH ROUTING

The existing multipath routing protocols were mainly developed to provide fault tolerance at the network level. Since providing fault tolerance was the primary motivation of utilizing multipath routing approaches for reliable data transmission over unreliable links, most of the early works on multipath routing technique fall in this category. As link and node failures are the main causes of path failures, the primary objective of these protocols is to guarantee certain performance parameters through preserving multiple alternative paths as the backup routes. This section introduces the research on the fault-tolerant routing using multipath routing approach. Directed Diffusion is a query-based routing protocol that uses the concept of multipath routing to provide path failure protection. Routing operation is initialized by the sink node through flooding interest messages throughout the network. These *interest* messages contain some information regarding to the task that should be performed by the sensor nodes. During this stage, all the intermediate nodes cache the interest messages received from their neighbors for later use. Moreover, upon reception of an interest message, the receiver node creates a gradient towards the node from which this message has been received. In this stage several paths can be discovered between each pair of source-sink nodes. After that, whenever a source node detects an event matched with the existing information in its interest table, it forwards its data packets towards the sink node through all the constructed gradients. The sink node receives its requested data through several paths with a low-data rate. Based on the packet reception performance over each path, the sink node can select the best path, i.e., the path with minimum latency, for data transmission. For this, the sink node reinforces the selected path by sending low-rate reinforcement messages towards the source node. Then, the source node merely transmits its data towards the sink node through the selected path. Furthermore, sink node continues to send low-rate interest messages over the remaining paths. This is to preserve the freshness of the established interest tables at the intermediate nodes, while it also maintains the discovered paths. When the active path fails to forward data packets, another available path can be used to provide fault-tolerant routing. Accordingly, whenever the data reception rate from the active path is reduced, the sink node reinforces the second available best path. Braided Multipath Routing Protocol is a seminal multipath routing protocol proposed to provide fault-tolerant routing in wireless sensor networks. This protocol uses a similar approach as Directed Diffusion to construct several partially disjoint paths. This protocol utilizes two types of path reinforcement messages to construct partially disjoint paths. Path construction is initiated through the sending of a primary path reinforcement message by the sink node to its best neighboring node towards the source node.

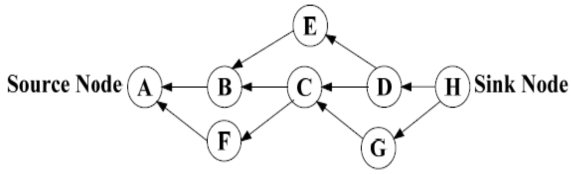

Fig 1: Braided Multipath Routing

For example, in Fig 1, the sink node sends the primary path reinforcement message to node D. When an intermediate node receives a primary path reinforcement message, it forwards this message to its best next-hop neighboring node towards the source node. This process is repeated until the primary path reinforcement message reaches the source node. In addition to the primary path construction process, source node and all the intermediate nodes along the primary path construct an alternative path around their next-hop neighboring nodes. This alternative path passes through the neighboring node, which is not included in the primary path. To this aim, whenever the sink and intermediate nodes send out the primary path reinforcement message, they also generate an alternative path reinforcement message and send this message to their next preferred neighboring node towards the source node. For instance, in Fig 1, the sink node sends an alternative path reinforcement message to node G in order to establish a backup path around node D. During this process, whenever an intermediate node, which is not a member of the primary path, receives an alternative path reinforcement message, it should forward this message to its best next-hop neighboring node. This process terminates upon reception of this message by one of the nodes along the primary path. As a result, each intermediate node along the primary path constructs a backup path around its next-hop neighboring node on the primary path via transmitting an alternative path reinforcement message. Through establishing a set of partially disjoint paths between the source and sink nodes, whenever the primary path fails to forward data packets towards the sink node, one of the constructed alternative paths can be utilized to avoid data transmission failure. Reliable Information Forwarding (ReInForm) Using Multiple Paths in Sensor Networks [3] uses the packet duplication technique to provide desired data transmission reliability for each application. In this approach, whenever a source node wants to forward its traffic towards the sink node, it first determines the required data transmission reliability based on the importance of the collected data. After that, the source node adds some information (e.g., local channel error rate, its hop count towards the sink node, and desired reliability) as Dynamic Packet State (DPS) fields to the data packets and sends multiple copies of the generated data packets over several paths. The source node determines the required number of paths to fulfill the reliability demands of the collected information according to the DPS fields of the data packets. During data transmission, all the intermediate nodes use the provided information by the DPS fields in the received data packets to determine the number of copies that should be transmitted to their next hop neighboring nodes. This process continues until all the transmitted data packets reach to the sink node. According to the main operation of this protocol, ReInForm tries to improve data transmission reliability through utilizing the packet duplication technique at all the involved sensor nodes in the data transmission process. N-to-1 Multipath Routing Protocol is proposed according to converging traffic pattern of wireless sensor networks. The main aim is to simultaneously discover multiple node disjoint paths from all the sensor nodes towards a single sink node. Furthermore, during data transmission phase, all the intermediate nodes utilize a packet salvaging technique at each hop to improve data transmission reliability. The entire routing operation in N-to-1 multipath routing protocol is performed through a simple flooding strategy in two stages. The sink node starts the first stage of the route discovery process through broadcasting a route update message. This stage, utilizes the main benefit of a simple flooding technique to construct a spanning tree and discover several paths from sensor nodes towards a single sink node. During this phase, each sensor node that receives a route update message for the first time, selects the sender of this message as its parent towards the sink node. In addition, if an intermediate node overhears a route update message from another neighboring node that introduces an alternative node-disjoint path through a different branch of the spanning tree, it adds this path to its routing table. This process continues until all the sensor nodes discover their primary path towards the sink node and a spanning tree same as Fig 2 is constructed through all the nodes.

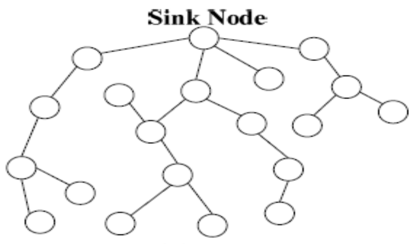

Fig 2: Spanning tree constructed by initial flooding in N-to-1 Multipath Routing protocol.

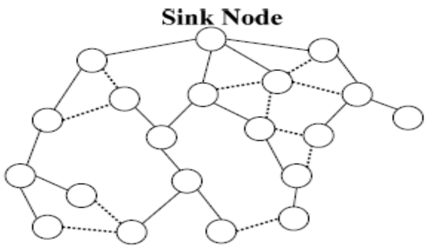

Fig 3: Multipath discovery using multipath extension flooding mechanism.

After that, the second stage of this protocol is initialized in order to discover more paths from each sensor node towards the sink node with the use of multipath extension flooding technique. As it can be seen from Fig 3, 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. Accordingly, the main purpose of employing multipath extension flooding technique in the second stage is to exchange some information regarding to the discovered node-disjoint paths in the first stage between the nodes belong to different branches of the constructed spanning tree. At the end of this stage, a routing tree similar to the Fig 3 is constructed by all the sensor nodes. Finally, source nodes split their traffic into several segments and distribute these data segments over the discovered paths. Reliable and Energy-Aware Multipath Routing is designed to mitigate the energy efficiency requirement of wireless sensor networks, which provides reliable data transmission through maintaining a backup path from each source node towards the sink node. Similar to the above presented protocols, the routing operation in this protocol is also initialized by the sink node. In this way, whenever the sink node receives an interest message from a source node and there is no active path towards the source node, it initiates a service-path discovery process through flooding a service-path request message. Upon reception of the service-path request message at the corresponding source node, the receiver node transmits a service-path reservation message towards the sink node (through the reverse path) to confirm the discovered path. While the service-path reservation message moves from the source node towards the sink node, whenever a node along the reverse path receives this message, it reserves a part of its residual battery level for data transmission over this path. The service-path construction process finishes by receiving the service-path reservation message at the sink node. Afterwards, the source node can transmit its data packets towards the sink node through the constructed path. After constructing the service-path, sink node initiates another path discovery process to establish a backup path towards the same source node by flooding a backup path discovery message. During this process, the intermediate nodes, which are not a member of the discovered service-path, broadcast the received backup path discovery message to their neighbors. Therefore, a node-disjoint path is created to provide fault tolerance in the case of service-path failure. H-SPREAD (Hybrid- Secure Protocol for Reliable data Delivery) combines the introduced path construction process in N-to-1 Multipath Routing Protocol with a hybrid data transmission technique to improve reliability and security of data transmission in wireless sensor networks. H-SPREAD takes advantages of a threshold secret sharing scheme and path diversity of multipath data forwarding to increase path resilient against node failure or compromised paths. According to the security property of the threshold secret sharing scheme, data packets can be safely forwarded towards the sink node even when a small number of nodes or paths have failed or are compromised during the data transmission process. In this algorithm, the source node divides each data packet to the multiple shares, M1, M2, M3,…, Mn, through using the secret sharing strategy and then transmits them towards the sink node through different paths. Based on the special characteristics of the threshold secret sharing mechanism, even when a certain number of paths have failed due to link or node failures, the original message can still be retrieved via other received shares at the destination node. Multipath Multispeed Protocol (MMSPEED) is designed based on the cross-layer design approach between network and MAC layer to provide QOS differentiation in terms of reliability and timeliness. From a timeliness perspective, MMSPEED extends the SPEED protocol through introducing multiple speed levels to guarantee timeliness packet delivery. The utilized speed notion in this protocol can be realized through Fig 4.

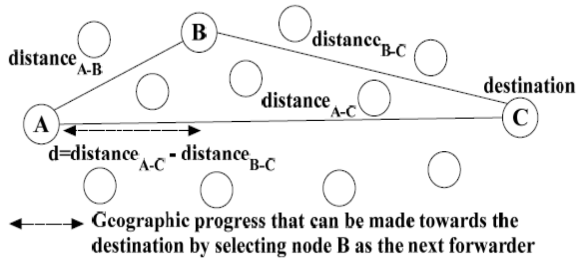

Fig 4: Progress speed from node A to node B towards the destination node.

Suppose node A forwards a data packet to its immediate neighboring node B, which can reduce the remaining geographic distance to the destination (i.e., node C) about d meters. According to the estimated delay of data transmission over link A–B (i.e., delayA-B), the achievable progress speed towards the destination through forwarding this data packet to the node B can be calculated as, SpeedA–B = (distanceA–C − distanceB–C)/delayA–B. In the reliability domain, reliability demands of different applications are satisfied through using a probabilistic multipath forwarding strategy. In this protocol, data packets are assigned to the appropriate speed layer to be placed in the suitable queue according to their speed category. After that, data packets are serviced in the FCFS policy. This mechanism ensures that high-priority packets are serviced before low-priority packets.

Therefore, MMSPEEAD benefits from a prioritized medium access mechanism through cross-layer interactions. According to the above descriptions, whenever a source node wants to forward a data packet towards the destination, it determines the speed requirement of the data packet based on its distance to the destination and its specified end-to-end deadline. Then, the classifier of the source node selects the corresponding speed layer that can meet the speed requirements of the data packet. The selected speed layer module performs all the subsequent routing decisions for data packet forwarding during the data transmission process. These routing decisions are made based on the amount of speed progress that can be achieved by each intermediate node. Furthermore, if an intermediate node receives a data packet and it perceives that this packet cannot meet its specified deadline through the selected speed layer, the receiver node can set another speed layer to satisfy the deadline requirement of the packet. From reliability perspective, MMSPEED benefits from path diversity property of multipath routing approach to guarantee reliability requirements of each data packet. This protocol provides reliability differentiation through controlling number of active paths and sending multiple copies of the original data packets over several paths. Accordingly, 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. Energy-Efficient Multipath Routing Protocol exploits the path diversity provided by multipath routing approach to prolong network lifetime by distributing network traffic over multiple node-disjoint paths. When an event occurs in the network, a sensor node in the event area is selected as the source node and initiates the route discovery process. Accordingly, the selected source node transmits multiple Route-request messages to its neighboring nodes. These Route-request messages include different path IDs to construct multiple node-disjoint paths from the selected source node towards the sink node. During the route discovery process, all the intermediate nodes select one of their best next-hop neighboring nodes towards the sink node. Upon reception of the first Route-request message by the sink node, it sets a timer to fulfill the path establishment process in an acceptable period. Therefore, all the paths discovered after the timer timeouts are considered as low-quality paths and the sink node discards the Route-request messages received from these paths. Then, the sink node assigns different data rates to the established paths using Equation (1). Sink node uses the ASSIGN messages to inform the selected source node about the assigned data rate of each path. Source node starts data transmission upon the reception of the ASSIGN messages:

$$r_j = \frac{R}{Pj} \sum_{i=1}^{N} pi, j=1, 2, \ldots, N \qquad (1)$$

Assuming N paths between a pair of source-sink nodes, rj data rate as shown in equation (1) is assigned to the j^{th} path, R is the requested data rate (by the application) that should be arrived at the sink node. *pi* and *pj* are the costs of i^{th} and j^{th} paths. The main advantage of this protocol is to prolong network lifetime by distributing network traffic over several paths according to the cost of data transmission over these paths. Multi-constrained QOS Multipath Routing (MCMP) is mainly designed to provide soft QOS guarantee in terms of reliability and delay. MCMP utilizes two different strategies to satisfy delay and reliability demands of wireless sensor network applications. During the route discovery process, all the intermediate nodes utilize equations to choose the neighboring node that fulfills the delay requirement of the intended application. To satisfy reliability, each node selects one or a set of its neighboring nodes, which additively provides the desired reliability towards the sink node. Therefore, at the end of the route discovery process, each source node has discovered a set of partially disjoint paths that can additively satisfy delay and reliability demands of the target application. Figure 8 demonstrates a set of discovered paths using MCMP protocol. According to the structure of the constructed paths, source and intermediate nodes, which have discovered multiple sub-paths towards the sink node, should send several copies of the original data packets to the sink node through different sub-paths to provide reliability. For instance, in Fig 5, node G should forward two copies of its received data packets towards the sink node through node H and node I.

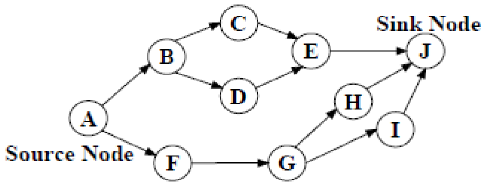

Fig 5: Partially disjoint paths established by MCMP.

Energy Constrained Multipath Routing (ECMP) [10] is the extended version of MCMP to provide energy-efficient communication, while it also satisfies the delay and reliability requirements of each application. In the MCMP protocol described earlier, intermediate nodes select the set of their neighboring nodes that satisfies the delay and reliability requirements of the data source, regardless of the energy consumed for data transmission over individual links. In contrast, ECMP introduces an energy optimization problem. This problem is constrained by delay, reliability and geo-spatial energy consumption to provide multi-constrained QOS routing in sensor networks. Accordingly, the main motivation in designing ECMP is to support multi-constrained QOS routing with minimum energy consumption. To demonstrate this issue, consider Fig 6, where node A has two neighboring nodes that can equivalently satisfy the delay and reliability requirements of the intended application.

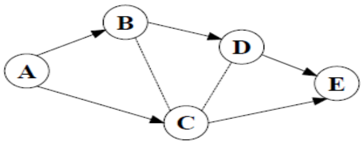

Fig 6: Link selection according to the Geo spatial energy consumption constraint.

As it can be seen from this figure, the distance between node A and node B is shorter than the distance between node A and node C. Since the required energy for data transmission can be related to the distance between sender and receiver, energy consumption for data transmission over link A-B is lower than the energy consumption for data transmission over link A-C. Therefore, selecting node B as the next-hop neighboring node A can result in lower energy consumption. Interference-Minimized Multipath Routing Protocol (I2MR) aims to support high-rate streaming in low-power wireless sensor networks through considering the recent advances in designing high-bandwidth backbone networks. I2MR tries to construct zone-disjoint paths and distributes network traffic over the discovered paths by assuming a special network structure and the availability of particular hardware components. All the deployed gateway nodes are assumed as the final destinations and it is supposed that these nodes are directly connected to the command center using non-interfering and high capacity links. In I2MR, the source node utilizes two paths for data transmission and keeps only one backup path towards the central command center. The route discovery phase includes three main steps: in the first step, each source node selects one gateway node as its primary gateway node and constructs the shortest possible path towards this gateway node. Then, in the interference-zone marking step, one and two-hop neighboring nodes of all the intermediate nodes along the first path are marked as the interference zone of the primary path. Finally, in the last stage, the primary gateway node determines the preferred quadrants from which the secondary and backup gateway nodes should be selected. Quadrants are determined based on the location of the source node. Furthermore, the preferred gateway nodes should be located beyond the interference range of the primary gateway node and they should have less distance to the source node than the other candidate gateway nodes. When the secondary and backup gateway nodes are determined, the source node starts to construct the secondary and backup paths through the nodes that are not marked as the interference zone of the primary path. At the end of the path construction process, source node loads the primary and secondary paths with the highest possible data rate and preserves the third path to achieve prompt packet recovery upon path failure. Maximally Radio-Disjoint Multipath Routing (MR2) utilizes an adaptive incremental technique to construct minimum-interfering paths, which satisfy the bandwidth requirements of multimedia applications. Additional paths are constructed whenever the active paths cannot provide the bandwidth requirements of the available network traffic. Like the other query-based routing protocols, the sink node initializes the route discovery process by flooding the network with a request message. Upon reception of the request message by the immediate neighboring nodes of the sink node, the receiver node adds its ID to the received request message as the path ID and rebroadcasts this message. Then, whenever a node receives a request message, it first checks the reported path ID and if it has not involved any path from the introduced source node towards the sink node, it should add the reported path to its routing table. Otherwise, if the included path ID in the received request message already exists in the routing table of the receiver, the introduced path should be replaced with the previous one if it provides a path with lower hop count. Then, source node starts packet transmission towards the sink node through the shortest discovered path. In order to address the mutual interference problem between adjacent paths, all the intermediate nodes along the active path should notify their neighboring nodes to act as the passive nodes in order to prevent them from participating in any route discovery process. Therefore, during the data transmission process, intermediate nodes that receive a data packet should send a bepassive message to all of their neighboring nodes except their next and previous-hop neighbors along the active path. Using this mechanism, whenever an additional path should be constructed (to provide sufficient bandwidth for data transmission), passive nodes are unable to respond to any request message. Energy-Efficient and Collision-Aware Multipath Routing Protocol (EECA) is an on-demand multipath routing protocol and uses the location information of all the sensor nodes to establish two collision-free paths between a pair of source-sink nodes. EECA aims to reduce the negative effects of wireless interference through constructing two paths in both sides of the direct line between the source-destination pair. Furthermore, the distance between these two paths is more than the interference range of the sensor nodes. In the first stage of the route discovery process, 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. After finding these neighboring sets, the source node broadcasts a Route-request packet towards these nodes to establish two node-disjoint paths. During the route discovery process, intermediate nodes utilize the same technique (used at the source node) to select their next-hop neighboring nodes and broadcast the received Route-request packet towards the sink node. Upon reception of a Route request packet by an intermediate node, the receiver node uses a back-off timer to restrict the overhead introduced by the route discovery flooding. Before broadcasting the received Route-request packet by the intermediate nodes, they set a back-off timer according to their distance from the sink node and their residual battery level. Neighboring nodes with higher residual battery and shorter distance to the sink node select shorter back-off timer. Therefore, at each stage of the Route-request flooding only one node wins to broadcast its received Route-request packet towards the sink node. Upon reception of the Route-request packet at the sink node, it sends a Routereply packet in the reverse path towards the source node. When the source node receives a Route-reply packet, it can transmit its traffic through the established path. Low-Interference Energy-Efficient Multipath Routing Protocol (LIEMRO) improves the performance demands of event-driven sensor networks through construction of an adequate number of interference-minimized paths. LIEMRO utilizes an adaptive iterative approach to construct a sufficient number of node-disjoint paths with minimum interference from each event area towards the sink node. Whenever an event occurs in the sensor field and there is no active path for data transmission towards the sink node, the selected source node starts to establish the first path by transmitting a Route request message towards the sink node. During this stage, source node and all the intermediate nodes select one of their next-hop neighboring nodes using Equations (2).

$$Next\_hop_i = \{ j \mid \forall j \in N_i \text{ and } cost_{ij} = \text{Min}_{j \in N_i} (Cost_{i,j})\} \quad (2)$$

$$Cost_{i,j} = (accETX_{i,sink}) \cdot \left(\frac{1}{resBatt_j}\right) \cdot (1+interferencelevel_j) \quad (3)$$

In Equation (2) N_i represents the neighboring set of node i. In Equation (3), $resBatt_j$ is the residual battery level of node j, $interferencelevel_j$ is the experienced interference level at node j, and $accETX_{i,sink}$ is the accumulated ETX value from node i to the sink node through neighboring node j. ETX value of a link is calculated as 1/pq, where p and q indicate the probability of successful forward and backward packet reception over that link, respectively. During the network initialization and neighbor discovery phase, the accumulated ETX value of all the sensor nodes towards the sink node are calculated through constructing the optimal spanning tree using the ETX cost. Upon reception of the first Route-request message by the sink node, it confirms the discovered path by forwarding a Route_reply message along the reverse path. While the Route_reply message moves from sink node towards the source node, whenever a node overhears this message it updates its interference level value based on the backward packet reception probability (i.e., q) of the node from which this message has been overheard. When the source node receives a Route_reply packet, it transmits its data packets through the constructed path and starts the construction of another path by sending a new Route-request message towards the sink node. Path construction process continues in an iterative manner as long as the sink node realizes that using a new path results in higher end-to-end throughput. Otherwise, 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 (i.e., when the source node receives a Route_reply packet), the source node transmits a portion of its traffic through this path using a quality based load distribution algorithm. The load balancing algorithm calculates the optimal traffic rate of the established paths based on their accumulated residual battery level, experienced interference level, and the probability of successful forward and backward packet reception over the links of a path. Energy-Efficient and QOS-based Multipath Routing Protocol (EQSR) is one of the proposed protocols designed to satisfy the reliability and delay requirements of real-time applications. EQSR improves reliability through using a lightweight XOR-based Forward Error Correction (FEC) mechanism, which introduces data redundancy in the data transmission process. Furthermore, in order to fulfill the delay requirements of various applications, this protocol utilizes a service differentiation technique through employing a queuing model to manage real-time and non-real-time traffic. EQSR initializes through broadcasting a HELLO message by all the sensor nodes. During this phase, sensor nodes collect information regarding to the cost of data transmission through their neighboring nodes. In the second phase of this protocol, the sink node starts the route discovery process by sending a Route-request message to its preferred neighbors using Equation (4) to select the most preferred next-hop neighboring node towards the source node from their neighboring set N. This process continues among the intermediate nodes until the source node receives a Route-request message transmitted by the sink node:

$$Next\_hop = \text{Max}_{y \in N_x} \{\alpha Eresd,y \beta Bbuffer,y + \gamma interfernce,xy\} \quad (4)$$

where N_x is the neighbor set of node x. $E_{resd,y}$ and $B_{buffer,y}$ indicate the residual battery level and available buffer size at neighbor y, respectively. $I_{interference,xy}$ is the experienced SNR over the link between node x and node y. All the sensor nodes calculate the values of these parameters for their neighboring nodes during the first stage of this protocol. Besides the primary-path establishment process, the sink node also starts to construct additional paths by sending subsequent Route-request messages to its next-preferred neighboring nodes. Whenever all the possible paths between a pair of source-sink nodes are discovered, a set of paths will be selected based on the probability of successful data transmission over each path. Furthermore, according to the propagation delay of the Route-request messages, EQSR estimates the data transmission delay of the paths and dedicates the best L paths for real-time traffic and the remaining paths for non-real-time traffic. At the last stage of this protocol, EQSR uses a lightweight XOR-based FEC algorithm to calculate Error Correction Codes (ECC) for data packets. Finally, the source node distributes its traffic over the selected paths according to their end-to-end delay. While EQSR reduces transmission delay and improves reliability, nevertheless, the FEC mechanism which is used to compute ECCs and retrieval of the original messages, imposes high control overhead. AOMDV-Inspired Multipath Routing Protocol is designed based on the multipath version of AODV (Ad hoc On-Demand Distance Vector) to achieve energy-efficient and low-latency communication in wireless sensor networks through using cross-layer information. Path construction is similar to the mechanism introduced in AOMDV with a few improvements. While AOMDV tries to discover all the possible link-disjoint paths between each pair of source-sink nodes, the AOMDV-Inspired Multipath Routing Protocol uses different routing table management strategy to construct only hop count optimal paths towards the destination node. With this protocol, the sink node confirms an additional path only if its first hop is different from the previously discovered paths and if this path provides the same hop count towards the sink node. Otherwise, if the sink node receives a Route-request message with the lower hop count than the existing routes (established from the same source node), it substitutes all the previously established paths by the newly discovered path.

V. SURVEY FINDINGS

Directed diffusion based networks are application aware. This enables diffusion to achieve energy savings by selecting empirically good paths and by caching and processing data in network. However, it has some drawbacks. First of all, for data aggregation it needs time synchronization technique that is not very easy to achieve in WSNs. Another problem is associated with the overhead involved in recording information thus increasing the cost of a sensor node. Simulation results in show the lower overhead of braided multipath routing approach compared to the idealized node-disjoint multipath protocol. Furthermore, through performance evaluation this protocol under a wide range of failure probabilities, it is demonstrated that this approach provides about 50% higher resilience against path failures, compared to the idealized node disjoint multipath protocol. However, since this protocol utilizes only one path for data transmission, the end-to-end throughput is limited to the capacity of a single path. Besides, since this approach is designed based on the principles of Directed Diffusion, the drawbacks of Directed Diffusion can be also applied to this protocol. Accordingly, the elevated reliability of the protocol in is achieved at the high cost of energy consumption and bandwidth utilization, which is in contrast with the primary demands of resource-constrained sensor nodes. The N-to-1 multipath routing protocol uses the broadcast nature of radio communications to construct several node-disjoint paths from sensor nodes towards the sink node without using additional control packets. This protocol also profits from the availability of several paths at the intermediate nodes to improve reliability of packet delivery by employing a per-hop packet salvaging strategy. Nevertheless, using such a simple flooding strategy cannot result in constructing high-quality paths with minimum interference. According to the operation of this protocol, all the constructed paths are located in physical proximity of each other and concurrent data transmission over these paths may reduce the network performance. Although Reliable and Energy-Aware Multipath Routing protocol provides energy-efficient and reliable data transmission, however it suffers from the main disadvantage of the alternative path routing strategy: the end-to-end capacity is limited to the capacity of a single path. More importantly, this protocol neglects the effects of wireless interference and link unreliability on the required energy for successful data transmission. Since the H-SPREAD approach utilizes the N-to-1 multipath routing algorithm to construct multiple paths, this protocol may suffer from the effects of wireless interference. Therefore, high packet loss ratio caused by interference can reduce the probability of successful packet retrieval at the sink node. Moreover, H-SPREAD only improves reliability and security of data delivery in the network, but it cannot enhance security of individual nodes. MMSPEED provides a probabilistic QoS guarantee in two different domains through combining geographic forwarding technique with a multipath routing approach. To satisfy different delay requirements, each intermediate node tries to forward its received data packet to the neighboring node, which is closer to the destination node in order to provide a good speed progress. However, according to the experimental results provided in, probability of successful data transmission over low-power wireless links highly depends on the sender-receiver distance and interference power of the receiver. Therefore, using geographic routing with greedy forwarding does not necessarily improve network performance metrics. Moreover, since data transmission over long links exacerbate the required energy for data transmission, this protocol cannot support long-life applications. The introduced data redundancy of MCMP is the main disadvantage of this protocol. Furthermore, since partially disjoint paths are usually located nearby, high data rate transmission causes significant interference. This highly affects the maximum achievable data transmission rate using this protocol. However, in MCMP, nodes randomly select their next-hop neighboring nodes without considering the amount of energy consumption over the chosen link. Therefore, compared to MCMP, ECMP refines the set of next-hop nodes to a smaller set through considering the energy efficiency of the links towards the neighboring nodes. Furthermore, the protocol proposed in uses a flooding strategy to estimate the experienced SNR over wireless links at the initialization phase and uses these values to discover the minimum interfering paths. However, the employed routing cost function cannot lead to the construction of interference minimized paths. In fact, using a simple flooding strategy during the neighbor discovery phase may exaggerate the exact value of mutual interference between different paths. On the other hand, as demonstrated in, a lower number of interference-minimized paths provide higher performance compared to the situation in which more number of paths is established without considering the effects of interference. Nevertheless, this protocol establishes and utilizes all the discovered node-disjoint paths. Maximally Radio-Disjoint Multipath Routing (MR2) protocol eliminates the negative effects of wireless interference by putting some nodes in the passive state. Simulation results confirm that MR2 improves the overall data reception rate at the sink node more than 70% and 30% compared to a multipath routing approach without interference-awareness and a single-path routing scheme, respectively. Still, this protocol suffers from two main drawbacks: first, MR2 is only suitable for query-driven applications; second, the utilized flooding strategy for constructing non-interfering paths imposes a high control overhead. Although EECA tries to discover the two shortest paths such that their distance from each other is more than interference range of the sensor nodes, it needs the nodes to be GPS-assisted and relies on the information provided by the underlying localization update method. These requirements increase the cost of network deployment and intensify the communication overhead, specifically in large and dense wireless sensor networks. In addition, as low-power wireless links exhibit significant signal variations over time, calculating the interference range of the sensor nodes based on the distance may not result in accurate interference estimation. Moreover, while transmitting data over minimum-hop paths can theoretically reduce end-to-end delay and resource utilization, however, using such paths in low-power wireless networks increases the probability of packet loss and intensifies the overhead of packet retransmission over each hop. LIEMRO improves the performance demands of event-driven applications through distributing network traffic over high-quality paths with minimum interference. This protocol utilizes a dynamic path maintenance mechanism to monitor the quality of the active paths during network operation and regulates the injected traffic rate of the paths according to the latest perceived paths quality. Therefore, it accounts for the temporal variations of the low-power wireless links and adjusts traffic distribution accordingly. However, similar to the most of the previously discussed protocols, LIEMRO does not consider the effects of buffer capacity and service rate of the active nodes to estimate and adjust the traffic rate of the active paths. The AOMDV does not introduce any load distribution mechanism to split network traffic over the established paths. AOMDV-Inspired Multipath Routing Protocol utilizes the information provided by the MAC layer to reduce data transmission latency. To this aim, during data transmission process, each intermediate node searches its routing table and forwards its received data packets to the next-hop neighboring node that wakes up earlier. While this MAC layer technique can reduce the transmission delay and interference, it requires all the sensor nodes to be aware about their neighboring nodes' timing information. Furthermore, similar to the ad hoc-based routing protocols, this protocol should flood the whole path information throughout the network during the route discovery phase. This flooding process imposes significant overhead to the resource-limited sensor nodes. The simulation results indicate the higher performance of I2MR compared to the standard AODV and a simple node-disjoint multipath routing protocol. However, the achieved performance improvement requires a special network structure and particular hardware components, which may not be feasible for many applications. In addition, due to the high complexity of the introduced zone-marking algorithm, this mechanism cannot effectively construct interference-minimized paths. Moreover, source nodes construct the three shortest paths (i.e., with minimum hop count) towards three separate gateway nodes to reduce the effects of wireless interference among the successive nodes along a path. However, due to the time-varying properties of low-power wireless links, data transmission over long hops results in increased packet loss ratio.

VI. ENERGY CONSUMPTION ANALYSIS

First directed diffusion is compared with two idealized schemes for data dissemination in networks. In the flooding scheme, sources flood all events to every node in the network, so diffusion is not significantly more energy efficient than flooding and it cannot be considered viable for sensor networks. In the omniscient multicast scheme, each source transmits its events along a shortest-path multicast tree to all sinks. Omniscient multicast approximately indicates the performance achievable in an IP-based sensor network. Fig 7 shows the average dissipated energy per packet as a function of network size. Omniscient multicast dissipates a little less than a half as much as energy packet per node as flooding. It achieves such energy efficiency by delivering events along a single path from each source to every sink. Directed diffusion has noticeably better energy efficiency than omniscient multicast. For some sensor fields, its dissipated energy is only 60% that of omniscient multicast. As with omniscient multicast, it also achieves significant energy savings by reducing the number of paths over which redundant data is delivered.

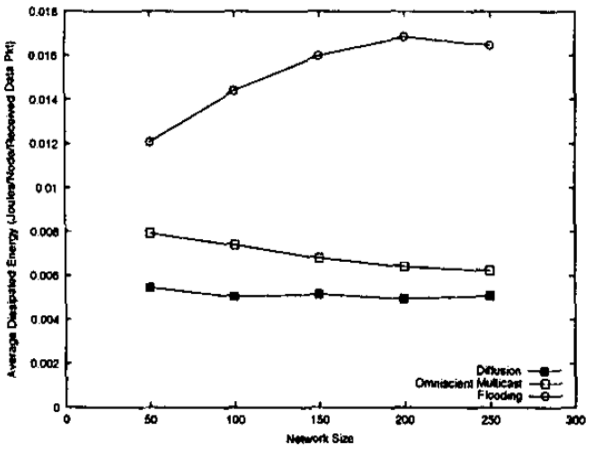

Fig 7: Average dissipated energy in directed diffusion compared to flooding and omniscient multicast.

Though flooding can be used to deliver packets with high reliability, the overhead incurred is significant. Using default routing for normal data and flooding for critical data does not provide a graceful transition, both in terms of attained reliability and incurred overhead. Also this kind of a scheme would overlook the fact that achieved reliability is heavily dependent on prevalent channel error rates. Any data dissemination protocol which is not adaptive to channel error rates and does not have a notion of information awareness would either be spending too much resource for unimportant information or would not be delivering really important information with high reliability. In ReInForM, based on the criticality of data inside a packet different priority levels are assigned. The main concept used was introduction of redundancy in data to increase probability of data delivery. This redundancy is in the form of multiple copies of the same packet which travels to destination among multiple paths. Use of dynamic packet state and randomized forwarding mechanism leads to use of all nodes in between the source and sink at random. It relies heavily on the existence of multiple paths from source to sink. Only if sufficiently large number of paths exists from source to sink without too much deviation in the number of hops from the optimal, the multipath approach would succeed. When number of paths between any two nodes is not sufficient for providing the reliability required, there may be more one copy of a packet per path. Fig 8 shows the overhead incurred in terms of number of packets transmitted for each of the three cases.

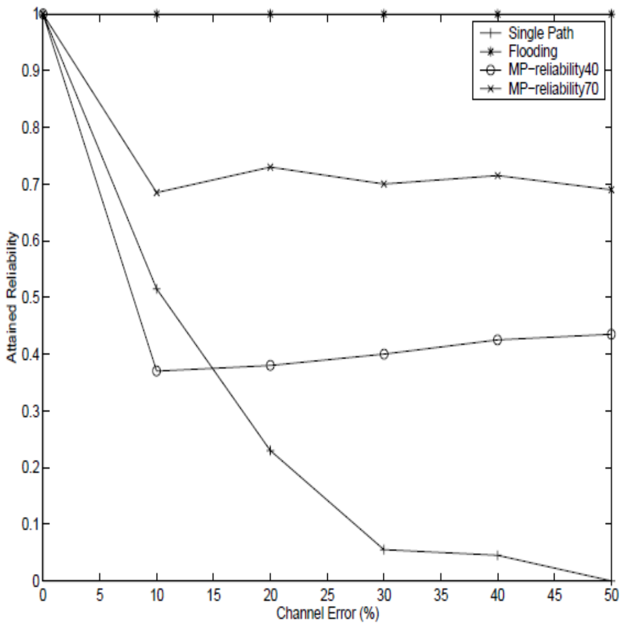

Fig 8: Overhead incurred by flooding, single path forwarding and multipath forwarding in ReInForM targeting 40% and 70% reliability for increasing channel error.

The overhead incurred by flooding is very high and that incurred by single path forwarding very low. The overhead incurred by the multipath forwarding schemes increases with the error rate but is significantly less than that of flooding even for an error rate of 50%. This experiment shows that even for small channel errors, the reliability provided by single path forwarding is very low. Flooding on the other hand incurs a huge overhead even when the channel conditions are good. The multipath forwarding scheme adapts to the network condition and provides desired reliability at a reasonable cost. We see that when the expected number of paths required providing desired reliability is close to the total number of nodes in the network (for example, with 60% error rate and required reliability of around 80%, the expected number of paths is well beyond 300 nodes), it is better to flood the network in a controlled manner, rather than rely on ReInForM which consumes more energy due to the increased overhead. In N-to-1 multipath route discovery protocol which distinguishes from other multipath routing protocols in that it is able to find multiple node disjoint paths from every sensor node to the base station simultaneously in one route discovery process. The distinct feature of N-to-1 multipath discovery protocol is that it is receiver-initiated and at the end of one route discovery process, the protocol finds every sensor node a set of node-disjoint paths to the base station simultaneously. It is highly efficient, with an average overhead of less than one routing message per path. It is observed that the flooding mechanism used could find disjoint paths without incurring any extra message exchanges. The results show that, in general, the routing protocol is highly efficient in terms of path finding as the per-path cost is less than one message. Since flooding is used in finding the paths, energy depletion remains as one of the important areas of concern. In response to the communication pattern in a WSN, H-SPREAD uses a novel N-to-1 multipath discovery protocol. Instead of finding multiple paths between a specific source and a specific destination, this N-to-1 multipath discovery protocol takes advantage of flooding in a typical route discovery process and finds multiple node-disjoint paths from every sensor node to the common destination simultaneously. However, since it uses the concept of flooding, its drawbacks also remain as drawback of the proposed scheme. In the MMSPEED protocol, whenever a source node wants to forward a data packet towards the destination, it determines the speed requirement of the data packet based on its distance to the destination and its specified end-to-end deadline. Then, the classifier of the source node selects the corresponding speed layer that can meet the speed requirements of the data packet. The selected speed layer module performs all the subsequent routing decisions for data packet forwarding during the data transmission process. This protocol provides reliability differentiation through controlling number of active paths and sending multiple copies of the original data packets over several paths. According to the experimental results, probability of successful data transmission over low-power wireless links highly depends on the sender receiver distance and interference power of the receiver. Since data transmission over long links exacerbate the required energy for data transmission, this protocol cannot support long-life applications.

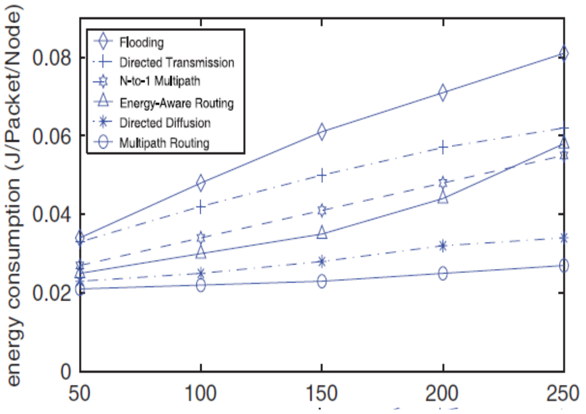

Fig 9: Average node energy consumption in energy efficient multipath routing

Fig 9 shows the simulation results the node energy consumption under different topology settings in Energy efficient multipath routing**.** We can observe that there is a lower node energy consumption of multipath routing over the other schemes. The flooding is the most costly protocol; by adding a simple mechanism of retransmission probability control on top of the flooding, the directed transmission improves the energy efficiency. The energy-aware routing obtains further improvement by calculating the retransmission probability as function of the node energy level and the hop distance to the destination. The multipath routing and directed diffusion perform better than other protocols. The better examined performance on directed diffusion is contributed by the capability of the protocol to find the path with the shortest delay. The periodic broadcasting of low-rate exploratory data from the source also helps changing to another route when the quality of the existing path degrades to a certain level. But the multipath routing protocol can maintain its node energy consumption at a low level even when the network size increases. For example, in Figure 9, compared to directed diffusion, the improvement of multipath routing is 1–34% when the network size increases from 50 nodes to 250 nodes. Experimental results demonstrate that the energy efficiency of multipath routing is stable and has little impact by the increase of the network size, while the performance of other schemes degrades with larger network size. In the MCMP protocol described earlier, intermediate nodes select the set of their neighbouring nodes that satisfies the delay and reliability requirements of the data source, regardless of the energy consumed for data transmission over individual links. In contrast, ECMP is designed to support multi-constrained QOS routing with minimum energy consumption. In MCMP, nodes randomly select their next-hop neighbouring nodes without considering the amount of energy consumption over the chosen link. Therefore, compared to MCMP, ECMP refines the set of next-hop nodes to a smaller set through considering the energy efficiency of the links towards the neighbouring nodes. In wireless sensor networks, bandwidth is one of precious resources to multimedia applications. To get more band- width, multipath routing is one appropriate solution provided that inter-path interferences are minimized. Maximally Radio-Disjoint Multipath Routing provides necessary bandwidth to multimedia applications through non-interfering paths while increasing the network lifetime. According to the simulation results, it consumes less energy especially for highly interfering and large networks. It is clear that energy saving will be better if we increase the simulation time. This is mainly due to the fact that a given number of nodes (passive ones) are put in the sleep mode.

In energy efficient and collision aware (EECA) node disjoint multipath routing algorithm, the main idea is to use the broadcast nature of wireless communication to avoid collisions between two discovered routes without extra overhead. Additionally, EECA restricts the route discovery flooding and adjusts node transmit power with the aid of node position information, resulting in energy efficiency and good performance of communication. The performance of EECA protocol relative to AODV under a group of network topologies and traffic scenarios shows that EECA achieved better performance in energy conservation in all the cases. A Low-Interference Energy-efficient Multipath Routing protocol (LIEMRO) for WSNs protocol is mainly designed to improve packet delivery ratio, lifetime, and latency, through discovering multiple interference-minimized node-disjoint paths between source node and sink node. LIEMRO includes a load balancing algorithm to distribute source node's traffic over multiple paths based on the relative quality of each path. Simulation results show that using LIEMRO in high traffic load conditions can increase data reception rate and network lifetime even more than 1.5 times compared with single path routing approach, while end-to-end latency reduces significantly. Accordingly, LIEMRO is a multipath solution for event-driven applications in which lifetime, reliability, and latency are of great importance. Satisfying Quality of Service (QOS) requirements for the different QOS based applications of WSNs raises significant challenges. The networking protocols need to cope up with energy constraints, while providing precise QOS guarantee. In Energy Efficient and QOS Based Routing Protocol for Wireless Sensor Networks, they propose an Energy Efficient and QOS aware multipath routing protocol that maximizes the network lifetime through balancing energy consumption across multiple nodes, uses the concept of service differentiation to allow delay sensitive traffic to reach the sink node within an acceptable delay, reduces the end to end delay through spreading out the traffic across multiple paths, and increases the throughput through introducing data redundancy. Simulation results have shown that this protocol achieves lower average delay, more energy savings, and higher packet delivery ratio than the MCMP protocol.

VII. CONCLUSION

This paper provides a comprehensive analysis of most of the proposed multipath routing protocols for wireless sensor networks. Nowadays, multipath routing techniques are considered an efficient approach to improve network capacity and resource utilization under heavy traffic conditions. With respect to the recent advances in the development of multipath routing protocols for wireless sensor networks, there is a need to investigate the significance as well as the detailed operation and classification of the proposed approaches. To fill this gap, in this paper we have attempted to identify the challenges pertaining to the design of multipath routing protocols for wireless sensor networks. In addition, we have highlighted the main advantages of using multipath routing approach to satisfy the performance requirements of different applications. Also, the paper provides an energy consumption analysis of various multipath routing schemes when compared to that of other routing schemes like flooding that are already present.

REFERENCES

[1] Intanagonwiwat, C.; Govindan, R.; Estrin, D. Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks. In Proceedings of the 6th Annual International Conference on Mobile Computing and Networking (MobiCom ’00), Boston, MA, USA, 6–11 August 2000; pp. 56–67.

[2] Ganesan, D.; Govindan, R.; Shenker, S.; Estrin, D. Highly-Resilient, Energy-Efficient Multipath Routing in Wireless Sensor Networks. Mobile Comput. Commun. Rev. 2001, 5, 11–25.

[3] Deb, B.; Bhatnagar, S.; Nath, B. ReInForM: Reliable Information Forwarding Using Multiple Paths in Sensor Networks. In Proceedings of the 28th Annual IEEE International Conference on Local Computer Networks (LCN’03), Bonn, Germany, 20–24 October 2003; pp. 406–415.

[4] Lou, W. An Efficient N-to-1 Multipath Routing Protocol in Wireless Sensor Networks. In Proceedings of the 2nd IEEE International Conference on Mobile Ad-hoc and Sensor System (MASS ’05), Washington, DC, USA, 7–10 November 2005; pp. 672–680.

[5] Hassanein, H.; Luo, J. Reliable Energy Aware Routing in Wireless Sensor Networks. In Proceedings of 2nd IEEE Workshop on Dependability and Security in Sensor Networks and Systems, Los Alamitos, CA, USA, 24–28 April 2006; pp. 54–64.

[6] Lou, W.; Kwon, Y. H-SPREAD: A Hybrid Multipath Scheme for Secure and Reliable Data Collection in Wireless Sensor Networks. IEEE Trans. Veh Tech. 2006, 55, 1320–1330.

[7] Felemban, E.; Lee, C.G.; Ekici, E. MMSPEED: Multipath Multi-SPEED Protocol for QoS Guarantee of Reliability and Timeliness in Wireless Sensor Networks. IEEE Trans. Mobile Comput. 2006, 5, 738–754.

[8] Lu, Y.M.; Wong, V.W.S. An Energy-Efficient Multipath Routing Protocol for Wireless Sensor Networks. Int. J. Commun. Syst. 2007, 20, 747–766.

[9] Huang, X.; Fang, Y. Multiconstrained QoS Multipath Routing in Wireless Sensor Networks. J. Wirel. Netw. 2007, 14, 465–478.

[10] Bagula, A.; Mazandu, K. Energy Constrained Multipath Routing in Wireless Sensor Networks. In Proceeding of the 5th International Conference on Ubiquitous Intelligence andComputing, Oslo, Norway, 23–25 June 2008; pp. 453–467.

[11] Teo, J.Y.; Ha, Y.; Tham, C.K. Interference-Minimized Multipath Routing with Congestion Control in Wireless Sensor Network for High-Rate Streaming. IEEE Trans. Mobile Comput. Mobile Comput. 2008, 7, 1124–1137.

[12] Maimour, M. Maximally Radio-Disjoint Multipath Routing for Wireless Multimedia Sensor Networks. In Proceedings of the 4th ACM Workshop on Wireless Multimedia Networking and Performance Modeling, Vancouver, BC, Canada, 27–31 October 2008; pp. 26 31.

[13] Wang, Z.; Bulut, E.; Szymanski, B.K. Energy Efficient Collision Aware Multipath Routing for Wireless Sensor Networks. In Proceedings of the 2009 IEEE International Conference on Communications (ICC’09), Dresden, Germany, 14–18 June 2009; pp. 91-95.

[14] Radi, M.; Dezfouli, B.; Razak, S.A.; Bakar, K.A. LIEMRO: A Low-Interference Energy-Efficient Multipath Routing Protocol for Improving QoS in Event-Based Wireless Sensor Networks. In Proceedings of the 4th International Conference on Sensor Technologies and Applications (SENSORCOMM ’10), Venice, Italy, 18–25 July 2010; pp. 551–557.

[15] Ben-Othman, J.; Yahya, B. Energy Efficient and QoS Based Routing Protocol for Wireless SensorNetworks. J. Parall. Distrib. Comput. 2010, 70, 849–857.

[16] Radi, M.; Dezfouli, B.; Bakar, K.A.; Abd Razak, S.; Nematbakhsh, M.A. Interference Aware Multipath Routing Protocol for QoS improvement in Event-Driven Wireless Sensor Networks. Tsinghua Sci. Tech. 2011, 16, 475–490.

