Energy Aware Multipath Routing in Wireless Sensor Networks

A thesis submitted in

in partial fulfillment of the requirements

for the degree of

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in

Computer Science & Engineering

by

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Dedicated to my Parents

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Certificate

This is to certify that the work in the thesis entitled *Energy Aware Multipath Routing in Wireless Sensor Networks* by *Pratik Agarwal*, bearing roll number 211*cs*2274, is a record of an original research work carried out by him under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of *Master of Technology* in *Computer Science and Engineering.* Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Sanjay Kumar Jena

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Abstract

Wireless Sensor Networks(WSNs) are made of sensor nodes with restricted battery life and transmission capability. In this work we propose an energy efficient multipath routing algorithm in WSN. This protocol is designed to improve the latency, resiliency and efficiency through discovering multiple paths from the source to the destination. It has a sink initiated Route Discovery process with the location information of the source known to the sink. There are two types of nodes which are used here one is primary and the other is alternate. At the end of the route formation one primary path and multiple number of alternate paths are built,and, all nodes except the primary are put to sleep mode which helps us to save energy and generate a collision free path, the primary path is used to transmit the data from source to the sink and if the route disrupts, the next best alternate route is used for the purpose and if no path exists between the source and destination then process starts from the beginning. Our simulation finds the latency, packet delivery ratio, average control packet overhead and total energy consumed. The proposed protocol has 12% (approx.) less control packet overhead in comparison to MR2 and LIEMRO,5% less average energy consumption in comparison to MR2 and 28% less average energy consumption in comparison to LIEMRO. Regarding latency the proposed protocol has similar result to MR2 but in comparison to LIEMRO the algorithm is 24% faster. Lastly in case of Packet Delivery Ratio the proposed protocol gives 5%(approx.) better result in comparison to MR2 and , 12% better result in comparison to LIEMRO on an average.

***Keywords*:** alternate path,energy efficient,multipath routing,primary path,Wireless Sensor Networks.

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Chapter 1

Introduction

A wireless sensor network is a collection of sensor nodes with limited power supply and constrained computational and transmission capability. Due to the limited transmission and computational ability, and high density of sensor nodes, forwarding of data packets takes place in multi-hop data transmission. Therefore routing in wireless sensor networks has been an important area of research in the past few years.

The sensor nodes run on non-rechargeable batteries, so along with efficient routing the network should be energy efficient with efficient utilization of the resources and hence this is an important research concern. Advances in wireless technologies and evolution of low cost sensor nodes have led to introduction of low power wireless sensor networks. Due to multiple functions and ease of deployment of the sensor nodes it can be used in various applications such as target tracking, environment monitoring , health care, forest fire detection, inventory control, energy management, surveillance and reconnaissance, and so on [1]. The main responsibility of the sensor nodes in a network is to forward the collected information from the source to the sink for further operations, but the resource limitations [2], unreliable links between the sensor nodes in combination with the various application demands of different applications make it a difficult task to design an efficient routing algorithm in wireless sensor networks.

Designing suitable routing algorithms for different applications, fulfilling the different performance demands has been considered as an important issue in wireless sensor networks. In these context many routing algorithms have been proposed to improve the performance demands of various applications through the network layer of the wireless sensor networks protocol stack [3, 4], but most of them are based on single-path routing. In single-path routing approach basically source selects a single path which satisfies the performance demands of the application for transmitting the load towards the sink.

Though the single path between the source and sink can be developed with minimum computation complexity and resource utilization, the other factors such as the limited capacity of single path reduces the available throughput [5]. Secondly, considering the unreliable wireless links single path routing is not flexible to link failures, degrading the network performance. Finding an alternate path after the primary path has disrupted to continue the data transmission will cause an extra overhead and increase delay in data delivery. Due to these factors single path routing cannot be considered effective technique to meet the performance demands of various applications.

To overcome these performance issues and to cope up with the limitations of the single path routing strategy , multi-path routing strategy also known as alternate path routing came into existence. As the name suggests there will be multiple paths established between the source and the destination through which the data can reach the destination [6]. Now how these links are used are totally based on the individual routing strategy. Some routing algorithms use the best path to send the data, keeping the other alternate paths as a backup and use it if the primary path fails, some use all the paths concurrently to send data and so on.

In the past few years multi-path routing approach is extensively used for different network management purposes, such as providing a fault tolerant routing, improving transmission reliability, congestion control and Quality of Service(QoS) support in the wired and wireless networks, but the unique features of the wireless sensor networks and the characteristics of the short range radio communications introduce a new challenges that should be addressed in designing the multi-path routing protocols.

1.1 Routing in WSN:

Since transmission of data from the targeted source to the sink is the main task of the wireless sensor networks, the method used to do the data forwarding is an important issue which should be considered in developing these networks.

Considering the unique features of low power wireless sensor networks, routing in WSN is much more challenging compared to traditional wireless networks such as ad-hoc networks [3, 4]. First, considering the high density of nodes, the routing protocols should route data over long distances, regardless of the network structure and size, in addition to the above requirement some of the active nodes may fail during the operations due to the environmental factors or energy depletion of sensor nodes or hardware faults, but these issues should not interrupt the normal operations of the network. Moreover, as mentioned earlier the wireless sensor nodes are restricted in terms of power supply, processing capability and available bandwidth, routing and data forwarding should be performed with effective network resource utilization. Further, considering the performance demands of the wireless sensor networks are totally application dependent, routing algorithms should satisfy the QoS demands of the application for which the network is being deployed. For example, challenges in designing the routing algorithms for environment monitoring will be different from issues that should be considered for health care monitoring or target tracking.

Based on the differences between wireless sensor networks and traditional wireless networks, various routing protocols were proposed over the past few years, to address the routing challenges introduced by the new features of the wireless sensor networks. AL-Karki et.al [3] classified the existing routing protocols in wireless sensor networks in two different perspectives, network structure and protocol operation.

From network point of view, routing algorithms are classified as flat, hierarchical and location based routing protocols.

Flat routing protocols are designed for network structure with homogeneous nodes meaning all nodes have the same transmission and processing capability. Directed Diffusion [7] , Sensor Protocol for Information via Negotiation (SPIN) [8], Rumour Routing [9], Minimum Cost Forwarding Algorithm(MCFA) [10] , Energy Aware Routing(EAR) [11] can also be added in this category.

In this group of protocols they demonstrate several advantages such as low topology maintenance overhead and the ability of multi-path discovery.

Another group of protocols is the hierarchical routing protocols which were proposed to increase the scalability of the network and make the network energy efficient through node clustering. In this group of protocols all the sensor nodes are grouped into clusters and each cluster will have a cluster head which will be responsible for the collection of data from its cluster nodes, data processing and then forwarding the data towards the sink. Though this structure provides high network scalability, clustering operation but the cluster head replacement impose high signaling overhead to the network. Several routing algorithms such as Low-Energy Adaptive Clustering Hierarchy(LEACH), Threshold-Sensitive Energy-Efficient Sensor Network Protocol(TEEN) fall in this category [2]

The next group of routing protocols utilize the exact location of the sensor nodes for the routing purposes. The geographic Location of the nodes can be obtained directly using Global Positioning System(GPS) devices or indirectly through exchanging some information regarding to the signal strengths received at each node. Since the localization requires special hardware support and also imposes significant computation overhead, this approach cannot be easily used in resource constrained wireless sensor networks. Geographic and Energy-Aware Routing(GEAR) and Geographic Adaptive Fidelity(GAF) can be referred as the geographic routing protocols.

From the protocol operation perspective, the existing protocols can be classified into negotiation based, query based, QoS based, multi-path based and coherent-based protocols.

Negotiation based routing protocols was designed to provide energy-efficient communication by reducing the data redundancy during data transmission. Each sensor adds a high level data description to its collected data and performs some negotiations with all its neighboring nodes to eliminate the redundant data packets. SPIN [8] is an example of such type of protocol.

In the query based routing protocols, the sink node sends a query throughout the network regarding the desired sensing task. If any node senses any related query it sends back the collected data through the reverse path. Directed Diffusion [7] and Rumor Routing [9] are two examples of the query-based routing protocols.

The next group of protocols are the QoS based protocols is mainly designed to satisfy the QoS demands(delay, reliability,bandwidth) of the different applications. The main aim of these types of protocols is to establish the trade off between the data quality and energy consumption. Sequence Assignment Routing(SAR), SPEED, Multipath Multi-SPEED(MMSPEED), Delay-minimum Energy-aware Routing Protocol(DERP) can be considered as the QoS-aware routing algorithms.

Multi-path Routing protocols in contrast to the single path routing protocols provide multiple paths between the source and sink, there are many routing algorithms that fall under this catagory, for example Braided Multipath Routing, N-to-1 Multipath Routing Protocol [2].

In the last group of protocols the coherent based protocols, as all the network nodes process the same flooded data in the network, the algorithms are based on coherent data processing to avoid flooding. In this group of protocols data packets are sent to the aggregators in order to reduce data redundancy. Routing algorithms such as Directed Diffusion, SPIN and SAR use data aggregation and can fall under coherent data processing -based routing protocols.

1.2 Multipath Routing in Wireless Sensor Networks

The restricted capacity and transmission capability of multi hop path and high dynamics of wireless links single path approach is not able to provide efficient data rate in transmission in Wireless Sensor Networks. To overcome these issues now a days multi-path approach is used extensively. As mentioned before multi-path routing has demonstrated its efficiency to improve the performance of wireless sensor and ad-hoc networks. In the following,we review the gain in performance,that can be achieved by using multi-path approach.

1.2.1 Reliability and Fault Tolerance

Due to time dependent characteristics of low power wireless links, changing network topology and interference, reliable data transfer is a challenging task [12]. The main idea behind using the multi-path routing approach is to provide path flexibility and reliable data transfer. Coming to the fault tolerance domain, whenever there is a link failure or a node failure and the sensor nodes are not able to forward data packet, it can benefit from the availability of alternate path. By this mechanism till an alternate path is available data forwarding can be continued without any interruption even in case of path failures. There are two approaches which can elevate the data transmission reliability.

The first approach says that we can send multiple copies of the same data through multiple paths, so that the reliability is improved and second is the Erasure Coding in which the source adds some header information to the actual data and forwards the generated data packet over different paths. To reconstruct the original packet at the sink at least certain number of transmitted data packets from each source should be received by the sink.

1.2.2 Load Balancing and Bandwidth Aggregation

Due to the resource limitations of Wireless Sensor Nodes, excessive traffic loads in the high data rate applications are prone to congestion, which highly influences the network performance [13, 14] To overcome this problem, data dissemination algorithms can benefit from the high density of nodes in the Wireless Sensor Networks, to increase the network capacity by employing more network resources. Multi-path routing approaches can provide the best solution for this purpose, by splitting the network traffic over several available path and reducing the probability of congestion.

1.2.3 QoS Improvement

QoS in terms of network throughput, end to end latency, and data delivery ratio are important objectives in designing multi-path routing protocols for different networks [6, 15]. For instance the discovered path can be utilized to distribute the network traffic based on the QoS demands of the specific application. As the critical data can be sent through higher capacity with minimum delay and others can be forwarded through non optimal paths.

1.3 Basic Principles in Designing Multipath Routing Protocols

There are several components in multi-path routing protocol to construct multiple paths and distribute the traffic over the discovered paths. The performance gains of the multi-path routing protocols are highly dependent on the ability of the proposed protocol to construct high quality, reliable paths.We describe these components in details.

1.3.1 Path Discovery

As we know that data transmission in wireless sensor networks are done in multiple hops so choosing the intermediate nodes for creating multiple paths from source to the destination is one of the most important task. Among the aforementioned parameters path disjointedness is the main criterion which is utilized by all the existing protocols. The path disjointedness is categorized as node disjoint, link disjoint and partially disjoint.

Node disjoint means there will be no common nodes in the discovered paths. Link disjoint paths may have several nodes in common, while there will be no shared link between the paths. Partially Disjoint paths include paths which share several links or nodes between paths.

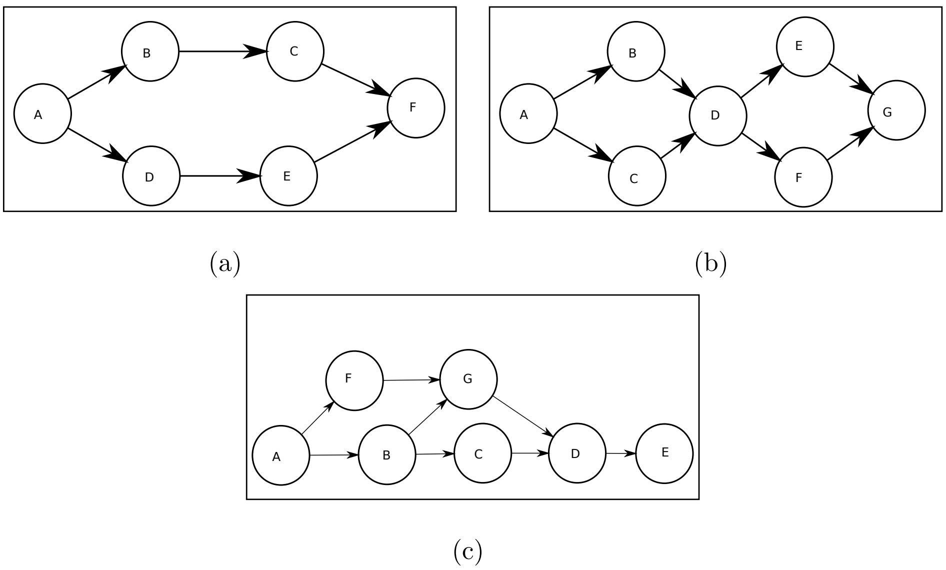


Figure 1.1: Various types of path disjointedness (a) Node-Disjoint Paths,(b) Link-Disjoint Paths and (c) Partially-Disjoint Paths

1.3.2 Path Selection and Traffic Distribution

After the construction of paths there are many factors which can be used to select a path from multiple paths to transmit data from source to destination. Some routing algorithms use the best path to transmit data and keep the others for backup, some may use the paths concurrently to transfer the data through multiple paths for reliability or even traffic distribution. The basic criteria considered for discovering a set of paths is the path disjointedness but due to time varying properties of radio communication and resource limitation, considering only this factor can lead to construction of some low quality paths. To overcome this problem in addition to the amount of path disjointedness various routing algorithms use various routing costs to make the best routing decision. Path length, packet loss rate, delay, residual battery level are some of the basic components of routing cost function. Once the set of paths is selected the routing protocol should determine how to distribute the network so that the resource utilization is maximized, improve performance demands such as throughput, data delivery ratio, delay, life time etc.

1.3.3 Path Maintenance

Due to the resource constraints of the sensor nodes and high dynamics of low-power links paths are highly error prone. Therefore there should be mechanism for path reconstruction to reduce performance degradation. The path discovery can start in three different situations,

1. When an active path has failed.
2. When all active paths have failed.
3. When certain number of paths have failed.

1.4 Applications of Sensors

1.4.1 Military Applications

The concepts of wireless sensor network is very closely related to the military applications. Regarding military applications the area of interest extents from information collection to enemy tracking, battle field surveillance or target tracking [16,17]. Classification algorithms use, for instance, input data that come from seismic and acoustic signal sensing [18].For example, in near future mines can be replaced by sensor nodes which will detect the intrusion of hostile units.An application related to this scenario, developed by the University of Virginia, is presented in [19]

Another demonstration, described in [20] deals with multi-vehicle tracking in the framework of a pursuit evasion game.

Ohio State University has demonstrated an application " An line in the Sand″ [21] in which ninety nodes are deployed which are capable of detecting metallic objects.

Palo Alto Research Center tries to spot "*interesting*″ vehicles (vehicles marked with specific way as important) by using sensor nodes equipped with microphones or steerable cameras [22].

In spite of being used in war times wireless sensor nodes can also be used in peace times such as homeland security,property protection and etc. [18].

1.4.2 Environment Monitoring

This is another important possible application of wireless sensor networks.

1. Indoor environmental monitoring
   Sensor nodes are deployed indoor to monitor light and temperature [23].The capability of sensor nodes to detect light, air pollution, frame status(windows and doors), air streams can be utilized for optimal control of indoor environment.

2. Outdoor environment monitoring

This is another very vast area of application of sensor networks such as measuring temperature, barometric pressure, humidity etc.. [24] shows an network for habitat monitoring, which was basically designed to monitor the natural environment of a bird.

1.4.3 Agricultural Applications

Sensor nodes are deployed in the agricultural fields with the firm motive of enhancing the efficiency and growth of cultivation. [25,26] describes the case of deploying sensor nodes in a vine yard, and how the sensor networks turned out to be useful for the farmers from the time of growing grapes to wine production and marketing.

1.4.4 Support for logistics

Wireless sensor networks are used in case of fleet management, that is tracing of lorries and tracking of parameters regarding carried goods [27].

1.4.5 Human Centric Applications

Human Science and health care systems can also benefit from the use of wireless sensor networks [18]. For example Intel's research concerns senior citizens and their problems [28].Cognitive disorders, which perhaps lead to Alzheimers, can be monitored and controlled at their early stages, using wireless sensors.

1.5 Motivation

In wireless communication media due to the resource constraint sensor nodes, reliable data delivery is a challenging task. If the route fails between source and sink, the routing protocol should be robust enough to recover from the failure. The existing multipath routing protocols provides reliability against the cost of energy. The proposed work is motivated by the flaws of the existing multipath routing protocols to make the network reliable & energy efficient.

1.6 Problem Statement

Given a Wireless Sensor Networks (WSNs) consists of n number of sensor nodes. Each sensor nodes works as a source or router. Let X and Y are source and sink respectively. Our objective is to propose an Energy Efficient Multipath Routing Protocol to provide resiliency and efficient data delivery from the source to the sink.

1.7 Organization of Thesis

Chapter 2, provides the Literature survey of the Energy Effiecient Multipath Routing Algorithms in Wireless Sensor Networks.
Chapter 3, provides the details of the proposed protocol **Energy Aware Multipath Routing Algorithm in Wireless Sensor Networks**.
Chapter 4, provides the simulation results of our proposed protocol **Energy Aware Multipath Routing Algorithm in Wireless Sensor Networks**.
Chapter 5, provides the conclusion.

Chapter 2

Literature Review

The ongoing research on multipath routing tries to cope up with fault tolerance and resource limitations of the low power sensor nodes through concurrent data forwarding over multiple paths. This section introduces some of the recent research in this area.

2.1 Directed Diffusion

Directed Diffusion [7] is a query based multi-path routing protocol, in which the sink initializes the routing process. The sink floods the *interest* message through the network, these *interests* contains information regarding the task which will be performed by the sensors. During the *interest* message flooding all the intermediate nodes store the interest message received from the neighbors for later use. As the *interest* message is received by the nodes, the receiver node creates a gradient [2] towards the node from which the message has been received. During this stage multiple paths can be discovered between each source-sink pair. After this stage, when the source finds an event matched with the existing information in the interest table it forwards the data through all the constructed gradients. Based on the performance of the the packet reception over each path the sink node selects a path, i.e. the path with minimum latency, the sink node reinforces the selected path by sending a low-rate reinforcement message towards the source. Then the source transmits the data through the selected path. Further the sink continues to send low-rate interest message over the remaining paths, this is done to preserve the freshness of the *interest* tables of the intermediate nodes, and also maintain the discovered paths. In case of failure of the active path the data can be forwarded through the other available paths providing fault tolerant routing.

2.2 Braided Multipath Routing Protocol

Braided Multipath Routing Protocol [29] was proposed to provide fault tolerant routing in WSN through constructing several partially disjoint paths similar to Directed Diffusion [7]. This protocol constructs partially disjoint paths using two path reinforcement messages, i.e. *primary path reinforcement message* and *alternative path reinforcement message*. The path construction is initialized by the sink by sending a *primary path reinforcement message* towards its best next-hop neighbor towards the sink, and this process continues till the *primary reinforcement message* reaches the source node. The source node and the other primary path intermediate nodes in addition to the *primary path reinforcement message* also send *alternative path reinforcement message* to the next best neighbor towards the source node which are not in the primary path constructing an alternative path along with the primary path. During this process an intermediate node which is not a member of a part of the primary path will choose the best next-hop neighbor towards the sink, and this process continues till the message reaches a node along the primary path. This process results in construction of backup paths from all the intermediate nodes which are in the primary path. Through establishment of partially disjoint paths whenever a primary path fails data can be forwarded through the alternate path.

2.3 Energy Efficient Multipath Routing

[30] is a distributed, scalable and localized multi-path search protocol to discover multiple node-disjoint paths between the sink and source nodes. It also contains a load balancing algorithm to distribute the traffic over the multiple paths discovered. It attains the path diversity provided by the multi-path routing approach to increase the network life time by distributing the traffic over multiple node-disjoint paths. When an event triggers in the network the sensor nodes exchange information between themselves and one of the sensors is selected as the source, after the source is selected, the source initiates a route discovery process. It transmits multiple Route-Request messages to its neighboring nodes. The Route-request message includes different path ID's to construct multiple node disjoint paths between the selected source and the destination,which should satisfy the following equation:

$$Next\_hop = argmin_{b \in N_a} \left\{ (1 - \frac{e_{b,residual}}{e_{b,init}})^{[\frac{\beta(1-(\Delta d+1))}{d_{ay}}]} \right\} \tag{2.1}$$

where N_a represents the set of neighbors of node a, d_{ay} represents the distance(hop count) between the node a and the sink node, d_{by} represents the distance between node b and the sink node, Δ d is the difference between d_{ay} and d_{by}, $e_{b,init}$ represents the initial battery level of node b, and β is the weight factor, and $\beta > 1$.

As the sink receives the first Route-request message, it sets a timer to complete the route establishment process.All the paths discovered after the timer expired are considered as low quality paths and the sink node discards the Route-request messages received from these paths. After the route establishment process the sink node assigns data rates to the established paths through the following equation.

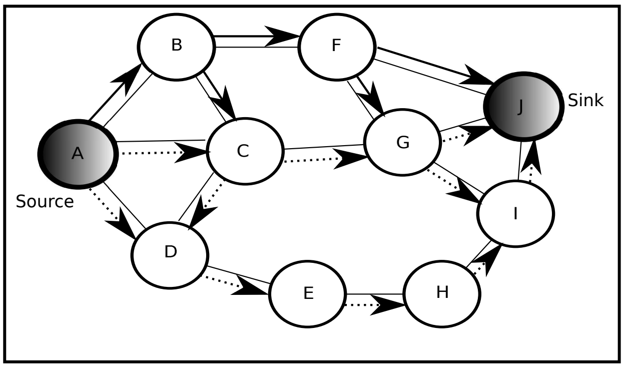
$$r_j = \frac{R}{p_j} \sum_{i=1}^{N} p_i, j = 1, 2, ...N \tag{2.2}$$

here it is assumed that there are N paths between the source-sink nodes, r_j is the assigned data rate to the j^{th} path, R is the data rate requested by the application which should arrive at the sink node. p_i and p_j are the cost of i^{th} and the j^{th} path. The sink node uses the $ASSIGN$ message to inform the selected source node about the data rate of each path . Source node starts data transmission as it receives the $ASSIGN$ message.

The main advantage of using the protocol is to improve the network life time by distributing the traffic over the network using the cost of transmission over these paths. The residual battery level of each node, their distances from the sink are among the main parameters which are used in the route discovery and the load balancing algorithm. However no measures are taken in regard to the interference level experienced by the intermediate nodes and its effect on the network performance. Nevertheless, this protocol establishes multiple node disjoint paths and use all the discovered paths.

2.4 AOMDV-Inspired Multipath Routing Protocol

AOMDV-Inspired Multi-path Routing Protocol [31] is designed based on the AOMDV(multi-path version of AODV, to attain energy efficient and low-latency communication in wireless sensor networks by using cross layer information.The mechanism used for path construction in this protocol is similar to the method introduced in AOMDV with some improvements.



AOMDV discovers all link-disjoint paths between each pair of source-sink nodes, whereas AOMDV-Inspired Multipath Routing Protocol uses hop-count optimal

Table 2.1: Constructed routing tables at the source node by AODV, AOMDV and AOMDV-Inspired Multipath routing protocols

AODV			
Node A's Routing Table			
Destination	Next−Node	Hops	Sequence No.
J	C	3	11

AOMDV Inspired Multipath Routing			
Node A's Routing Table			
Destination	Next−Node	Hops	Sequence No.
J	C	3	11
J	B	3	11

AOMDV			
Node A's Routing Table			
Destination	Next−Node	Hops	Sequence No.
J	C	3	11
J	B	3	11
J	D	5	11

paths toward the sink node.In this protocol the sink node confirms a new path only if the first node is different from the previously discovered paths, and if the provided hop count is the same as the previous one. And if the sink receives a Route-request with lower hop count then it replaces all the previously discovered paths with the newly discovered path. AOMDV does not provide us with any load balancing algorithm to split the traffic over the discovered paths. AOMDV-Inspired Multipath Routing Protocol uses the information from the MAC layer to reduce data transmission latency. For this purpose each node searches its neighbor table for the node which wakes up the earliest and forwards the data to the node. Though the information coming from the MAC layer can reduce the transmission delay and interference, but for this purpose all the sensor nodes needs to keep the updated timing information of all its neighbors. Further this protocol floods the whole path information through the network during the route discovery process. This mechanism of flooding imposes an extra overhead to the resource constraint sensors.

2.5 Interference-Minimized Multipath Routing Protocol

Interference-Minimized Multipath Routing Protocol (I2MR) [32] aimed to support high data rate streaming in wireless sensor networks through considering the recent advances in designing the high bandwidth backbone network. I2MR assuming a special network structure and with the availability of a particular hardware component tries to construct zone disjoint paths and distributes the traffic over the discovered paths.

All the deployed gateway nodes are assumed as the final destinations and it is assumed that these nodes are directly connected to the command center using non-interfering and high capacity links. The source node uses two paths to transfer data and keeps only one backup path to the central-command center.

Their are basically three main steps in the route discovery process.

1. each source selects one gateway node as its primary gateway node and construct the shortest path towards this gateway node.

2. Basically, called the $interference-zone$ marking steps all the one-hop and two-hop neighbors of the intermediate nodes along the first path are marked as the interference zone of the primary path.

3. In the final step the primary gateway determines the preferred quadrants from which the secondary and backup gateway nodes should be selected.

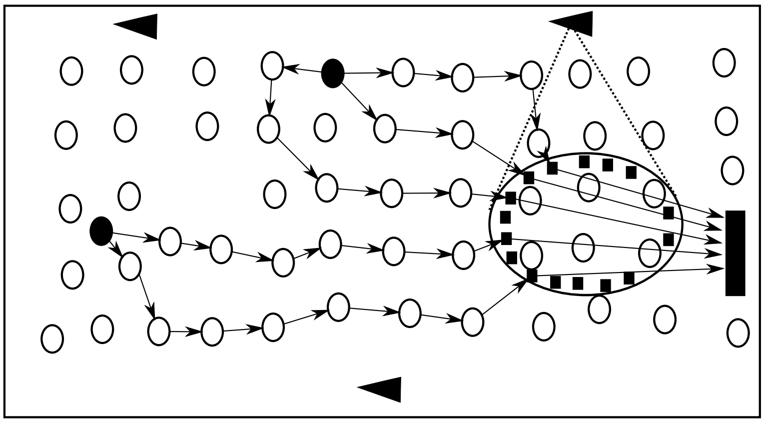


Figure 2.1: Assumed network structure in the design of I2MR. Constructed paths between each source node and the command center are demonstrated

The quadrants are decided based on the location of the source node, furthermore the preferred gateway nodes should be located beyond the interference range of the primary gateway and should have less distances to the source node than the other candidate gateway nodes. As the secondary an backup nodes are determined, the source starts the construction of the secondary and the backup paths using the nodes that are not marked in the interference range of the primary path.

After the completion of path construction the source node uses the primary and secondary paths with the highest possible data rate and keeps the third path to achieve prompt recovery upon path failure.During data transmission if an intermediate node detects an long congestion then it should notify the source to reduce the assigned data rate.

The simulation results of I2MR indicate higher performance as compared to standard AODV and simple node disjoint multi-path routing protocol, but the achieved improvements require special network structure and particular hardware support which may not be feasible for many applications. In addition to this the zone-marking algorithm adds high complexity to the system, due to which this mechanism cannot effectively construct interference-minimized paths.

Moreover, the source node creates three separate shortest paths towards three different gateways to reduce 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 rate.

2.6 Maximally Radio-Disjoint Multipath Routing($MR2$)

[33] addresses the problem of both inter-session and intra-session interferences, basically it adapts an incremental approach to construct minimum-interfering paths, to satisfy the band width requirements of the multimedia applications. It adapts an incremental approach to construct paths from the source to sink and in a given session only one path is built at once. Additional paths are built in case of congestion or in the case of bandwidth shortage. Interference awareness can be achieved by putting a subset of nodes in passive state, which do not take part in the routing process.

Like the other query based routing protocols, the sink node floods the route-request message to initiate the route-discovery process. Upon the reception of the route request by the immediate neighbors of the sink node it adds its ID to the received request as its path ID and rebroadcasts the message. Then whenever a node receives a route request message it checks whether the reported path ID, if any path does not exist between the introduced source node towards the sink node, it should add the reported path ID in its routing table, otherwise if the requested ID is already a part of the routing table it can be used for the updating the routing table if it provides a better metric(i.e. hop count) than the previous one. If the route request causes an update in the routing table the receiver node should rebroadcast the request message. The process continues till the source which contains the requested data receives the request message. At this time, the source transmits data through the best metric path(lowest hop count path). To address the interference problem all the intermediate nodes of the active path notify its neighbors to act as passive nodes. In order to prevent them from taking part in the route discovery process. Therefore, during data transmission process the nodes which receive the data packet should send a *bepassive* message to all its neighbors except from the source from where the message has arrived and the immediate next-hop node along the active path. This mechanism provide sufficient bandwidth for data transmission as the passive nodes are not able to answer to any request message.

Though this protocol eliminates the negative effects of the interference by putting a subset of nodes in passive state. The main drawback lies that this protocol is only suitable for query driven application, secondly, the flooding technique used in the route discovery process imposes a high control overhead.

2.7 Energy-Efficient and Collision-Aware Multipath Routing Protocol($EECA$)

Energy Efficient and Collision Aware Multipath Routing Protocol [34] is an on demand multipath routing protocol which uses location information of the nodes to establish two collision free paths on both sides of the direct line between the source-sink pair. Interference effects are reduced by keeping the distance between the two paths more than the interference range of the sensor nodes.

In the first stage the source finds two distinct set of nodes on both sides of the direct line between the source-sink pair. The source node after finding the neighbor set broadcasts a Route-request packet towards these nodes to discover two node disjoint paths. During this step the intermediate nodes also follow the same technique as the source node to select there next hop. Upon reception of a route request message the intermediate node set a back-off timer to restrict the overhead of the route discovery flooding. Before broadcasting the received route request message the intermediate nodes set a back-off timer based on their distance to the sink and

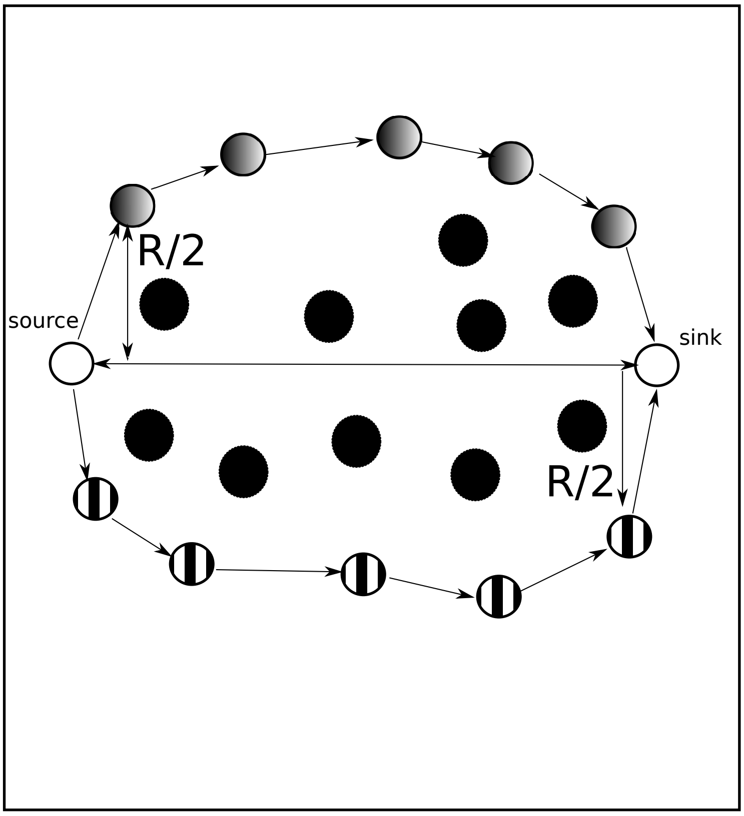


Figure 2.2: An example of the constructed paths by EECA.

residual battery level. The neighbor nodes with shorter distance to sink and high battery level set shorter back-off time , therefore, at each stage only a single node wins to broadcast the received Route-request packet towards the sink node. The sink node on receiving the route request sends a route reply in the reverse path towards the source. When the source receives the route reply it starts the data transmission through the established path.

Though EECA discovers two shortest non-interfering paths from the source to sink but still it needs the sensors to be assisted by The GPS and relies on the information provided by the underlying localization update method. These requirements increase the cost of the deploying the network and also increase the communication overhead, specially in dense and large wireless sensor networks. Secondly, the low-power wireless links exhibit signal variation over time, calculating the interference range of the sensors based on distance may not provide accurate result of interference estimation. Thirdly, transmitting data over minimum hop paths can reduce delay and resource utilization but using these paths can result in packet loss and an overhead of packet retransmission.

2.8 Low-Interference Energy Efficient Multipath Routing Protocol ($LIEMRO$)

LIEMRO (Low Interference Energy Efficient Multipath Routing) [35, 36] was basically designed to improve the packet delivery ratio, latency, and lifetime through multiple interference-minimized node disjoint paths. In addition it includes a load balancing algorithm to distribute the source node traffic over multiple paths based on relative quality of each path. Initially all nodes have information about their neighbor nodes and each node sends a limited number of control packets to the neighbors and look for number of successfully received packets from the neighbors and they also calculate the cost of the link which is done by the ETX metric. The route discovery phase is initialized when some event is discovered in the network, and to start the route establishment the source sends the route request from source to the sink, the nodes select the next hop using the following equation 2.3 and 2.4

$$Next\_hop_i = \{j|\forall j \in N_i and Cost_{i,j} = Min_{j\in N_i}(Cost_{i,j})\} \tag{2.3}$$

$$Cost_{i,j} = (accETX_{i,sink}).(\frac{1}{ressBatt_j}).(1 + interferenceLevel_j) \tag{2.4}$$

In Equation 2.3 N_i represents the neighboring set of node i. In Equation 2.4, $ressBatt_j$ 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 through the neighboring node j.ETX value is calculated using equation 2.5 where p and q are the probability of successful forward and backward reception over the link.During the network initialization phase accumulated ETX is calculated through constructing the optimal spanning tree using the ETX cost.

$$ETX = 1/pq \tag{2.5}$$

As the sink node receives the first route request packet, it confirms the discovered path by sending Route-reply through the reverse path. On the way from the sink to the source whenever a node overhears this message it updates its interference level value based on the backward reception probability, the node from which the message has been overheard, when the source node receives the Route-reply message it forwards the data through the established path, and starts the construction of a new path by sending a new Route-request packet towards the sink node. This is an iterative process and source continues to build new paths as long as the new path provides higher end to end throughput, otherwise if the last established path reduces the end to end throughput, the sink node asks the source to disable the last constructed path. Upon receiving the Route Reply from the new path the Source node divides the network traffic and send some portion of the traffic through this path using a quality based load distribution algorithm. The algorithm proposed for the Load Balancing Algorithm calculated the optimal traffic rate based on the accumulated residual battery level, the interference level experienced, and the probability of successful forward and backward packet reception over the links.

LIEMRO improves the performance demands of event driven applications through distributing the traffic over the network high quality paths with minimum interferences. It uses dynamic path maintenance mechanism to monitor the quality of paths during network operations and regulates the traffic rate according to the quality of paths, but LIEMRO does not consider the buffer capacity and service rate of the active nodes to estimate and adjust the traffic rate of the active paths.

Chapter 3

Energy Aware Multipath Routing in Wireless Sensor Networks

The proposed protocol named Energy Aware Multipath Routing [37] in Wireless Sensor Networks is based on the multipath scheme where multiple route exist between each source and the sink. In the following section we discuss system model and assumptions for the proposed protocol and working principle of the proposed protocol.

3.1 Network Model and System Assumption

There are n number of sensor nodes and a sink node in the network. After the deployment the nodes has to be stationary. We consider the sink node is in the middle of the network and static in nature. The sink node possesses unlimited computation, memory, and battery power. Each node knows their position, and the sink node contains the ID and *location* of the source node in the network. Sensor nodes are densely deployed and all are homogeneous. Each nodes communication range are identical and predefined.

3.2 Energy Aware Multipath Routing

We propose a routing algorithm which avoids flooding and takes the benefit of both load balancing and collision aware mechanism for energy conservation. Proactive routing protocol is preferred for the static network, but it is not advisable for the resource constrained sensor network,because in proactive protocols each node broadcasts messages to the entire network if there is a change in the network topology to keep the updated information and hence incurs an extra overhead. So we construct the route between source and sink when actually sink need the data from a particular source node. With this requirements we design a multipath routing algorithm for WSN. It mainly consists of three phases: Neighbor Discovery, Multipath Construction, and Data Transmission.

3.2.1 Neighbor Discovery

In this phase every node broadcasts a control packet contains their node ID, residual energy, and the location and wait for the neighbor discovery control packets from the nodes of its range to find the neighbor nodes. After the neighbor discovery phase each node finds its neighbor nodes. Now every node has the partial view of the network as illustrated in the Figure 3.1 .

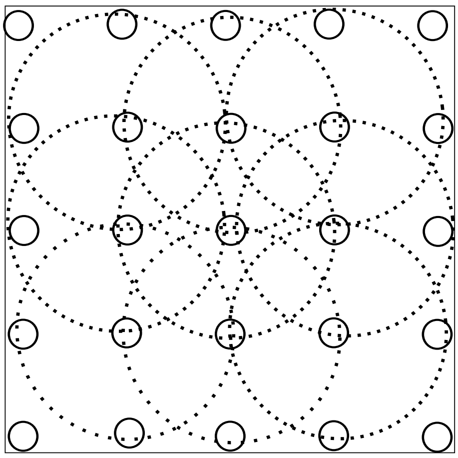


Figure 3.1: Neighbor Discovery

3.2.2 Multipath Construction

After the Neighbor Discovery phase, each node possesses their neighbor information and then the Multipath Construction phase starts. We assume that the source node location is known to the sink and based on the location of the source the sink starts the route request process. In this the main concept is that, there are two type of nodes *primary* and *alternate*. A node is a primary node if it is in the primary path from source to sink else if it is the part of any alternate path then it is the alternate node. As described in the Algorithm 1, the primary nodes find two paths to the source, the primary path and the alternate path. The primary path is built with the best possible neighbor (having the minimum Location Factor(LF)) and the alternate path is constructed with the next best neighbor (having the next minimum Location Factor(LF) after the primary path node).The alternate nodes find one single path towards the source node and searches its neighbor table for the node with minimum Location Factor(LF) and will prefer a primary node if possible, this is done to converge the path else the path can diverge from its direction toward the source, Next hop is chosen by the following equations 3.1 and 3.2

$$Next\_hop_i = min(LF_i) \tag{3.1}$$

$$LF_i = (Loc_{source} - Loc_b) \forall b \in Neighbor_i \tag{3.2}$$

where, LF_i is the set of distance of all the neighbors of node i from the source. Loc_{source} is the location of the source node,Loc_b is the location of the node b,and $Neighbor_i$ is the neighbor set of node i.

Here it is an incremental approach from the sink to the source. First the sink node which is itself a primary node, selects two neighbors based on the equation 3.1. Out of these two neighbor nodes one with the minimum location factor becomes the next primary node and the node with the second minimum location factor becomes the alternate node,and with this step we initialize the multipath construction phase. As shown in figure 3.2(a), node a which is connected by bold line has the minimum

Algorithm 1 **Multipath Construction**

Input: Set of n sensor nodes randomly distributed.

Output:One primary and multiple alternate paths from source to sink.

```
repeat
    if (node == sinknode) then
        FindPrimaryPath();
        FindAlternatePath();
    else if (node == Primary) then
        FindPrimaryPath();
        FindAlternatePath();
    else if (node == Alternate) then
        FindPrimaryPath();
    end if
until (node ≠ Source)

procedure FindPrimaryPath()
    if (node == Primary) then
        Broadcast PRIMARY;
        Search for the best node;
        node ← Primary;
    end if
    if (node == Alternate) then
        Broadcast ALTERNATE;
        Search for the best node and prefer Primary;
        if (node ≠ Primary) then
            node ← Alternate;
        end if
    end if
end procedure

procedure FindAlternatePath()
    if node == primary then
        Search for the next best path node accept Primary;
        if ((node ≠ Primary)&&(node ≠ Alternate)) then
            node ← Alternate;
        end if
    end if
    if (node == Alternate) then
        Exit();
    end if
end procedure
```

location factor, signifies a primary node and is in the primary path towards the source. Similarly node b is connected by dashed lines has the second minimum location factor is the alternate node and is the part of the alternate path towards the source node. All the intermediate nodes follow the same process as the sink node to find their corresponding neighbors till the source node is reached, this process is illustrated in the figures 3.2(b), 3.2(c), 3.2(d) and 3.2(e). Finally when the route request reaches the source node we see that one primary path and multiple alternate paths are constructed between the sink and the source node, which is shown in the figure 3.2(f).

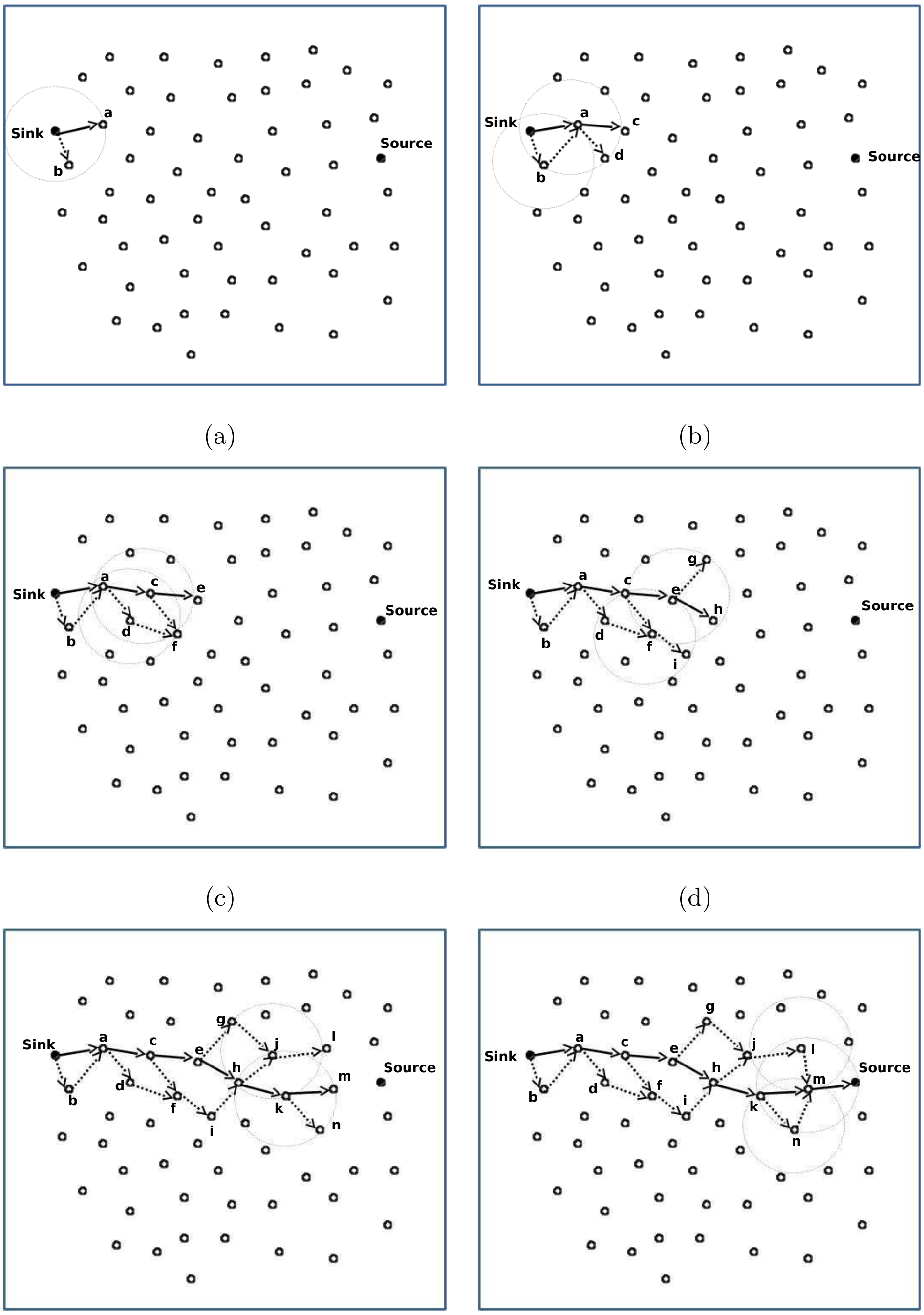
Algorithm 1 has two procedures $FindPrimaryPath()$ and $FindAlternatePath()$ which are repeated till the route request reaches the source node.

$FindPrimaryPath()$: This function is called by both primary and the alternate nodes. If the node is primary node it will broadcast its node type to be *primary* among its neighbors and search the node with minimum location factor in direction of the source node. Similarly if its an alternate node it broadcasts its node type to be alternate and finds the node with minimum location factor towards the source and will prefer the primary node if possible, so that the path converge instead of diverge. In both the above cases the found neighbor nodes can have two possible node types,

1. the node can be a primary node
2. or it can be an alternate node

else it has not been assigned any node type. If the parent node is a primary node then the node type of the found neighbor in any of the above cases will be changed to primary node. In case the parent node in an alternate node,the node type of the found neighbor will not changed if it has already been assigned a node type, and in case it has not been assigned any node type, the node will be assigned as alternate node.

$FindAlternatePath()$: This function is called only by the Primary nodes for



(a) (b) (c) (d) (e) (f)

Figure 3.2: Multipath construction steps are in figure (a),(b), (c), (d), (e) and (f)

finding an alternate path towards the source. It finds the next best node which is called alternate node and add it in its path.

In the algorithm all nodes except the primary nodes are put to sleep mode. At a time there is only one active path between the source node and the sink node. This is done to reduce interference from other paths and avoid collision. Both of these factors help to save energy. If the primary path disrupts the protocol selects the alternate path with the best metric(e.g. hop count) to transmit data, and if all path disrupts and no path is left between the source and sink then again the process starts from the Neighbor Discovery phase.

3.2.3 Data Transmission

After the route discovery by the multipath construction phase data transmission takes place between source and sink. The primary and alternate paths are available, but the data transmitted only over the primary path. Source utilise alternate path when primary path is not available. Rest of the nodes that are not in the active path will go to sleep mode to conserve energy. If there will be no path exist between source and sink, the process of route discovery starts.

3.3 Energy Model

Energy modeling in WSN is based on the theoretical energy consumption of the existing platforms. We have considered three modes of energy consumption, first the energy consumed due to transmission of packets (Eq 3.3), secondly, energy consumed due to reception of packets (Eq 3.4),third, energy spent spent by nodes in the idle mode (Eq 3.5) and finally the energy consumed by the nodes in processing.

$$Energy_{Transmission} = Energy_{XT} \times t(bits) + E_{XP}(d^2) \tag{3.3}$$

$$Energy_{Receiving} = E_{XR} \times t(bits) \tag{3.4}$$

$$Energy_{Sleep} = E_{XS} \times t(sec) \tag{3.5}$$

$$TotalEnergy = Energy_{Transmission} + Energy_{Receiving} + Energy_{Sleep} \tag{3.6}$$

In Equations 3.3, 3.4 and 3.5 $Energy_{XT}$ refers to energy consummed per bit for transmission, E_{XR} is the energy consumed per bit for receiving, and E_{XS} is the energy consumed per second in idle mode and $E_{XP}(d^2)$ is the energy consumed in finding the next hop neighbor.

Chapter 4

Simulation and Results

4.1 Simulation Parameters

Table 4.1: Simulation Parameters

Simulator	**Castalia**
Simulation Area	**100 m * 100 m**
Number of Nodes	$20, 30, 40, 50$
MAC protocol	**TMAC**
Initial battery capacity	$18720 joule$
Simulation duration	$600 seconds$
Size of packets	$32 bytes$
Output power	$-3 dBm$
Number of runs	5

The Energy Aware Multipath Routing Protocol is implemented in Castalia. Castalia [38, 39] is a simulator for Wireless Sensor Networks (WSN), Body Area Networks (BAN) and generally networks of low-power embedded devices. It is based on the OMNeT++ platform. We also implemented an interference-aware routing protocol(MR2) and Low Interference Aware Multipath Routing Protocol(LIEMRO) and we have considered the following simulation parameters as mentioned in Table 4.1 for all the algorithms.

4.2 Performance Parameters

The protocol Energy Aware Multipath Routing Protocol is designed and compared with the existing algorithms on the basis of the following performance metrics.

4.2.1 Packet Delivery Ratio

The ratio of the number of delivered data packet to the destination as shown in Equation 4.1. This illustrates the level of delivered data to the destination.

$$PDR = \sum Numberofpacketreceive / \sum Numberofpacketsent \tag{4.1}$$

The result is shown in Figure 4.1. The proposed scheme Energy Aware Multipath Routing gives the proposed protocol gives improvement of 5% (approx.) over MR2 and, 12% over LIEMRO.

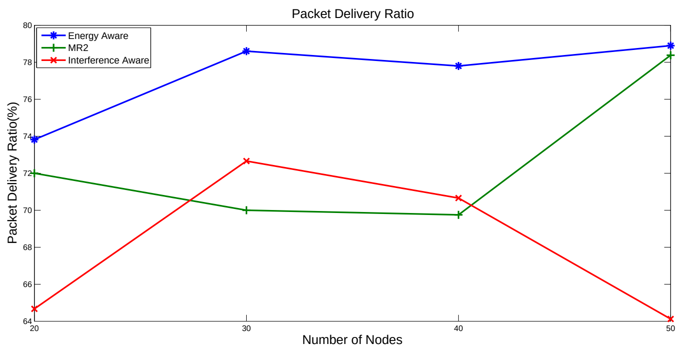


Figure 4.1: Packet Delivery Ratio

4.2.2 End-to-end Delay

The average time taken by a data packet to arrive in the destination. It also includes the delay caused by route discovery process and the queue in data packet transmission. Only the data packets that successfully delivered to destinations that counted.

Regarding latency the proposed protocol has similar result to MR2 but in comparison to LIEMRO the algorithm is 24% faster.

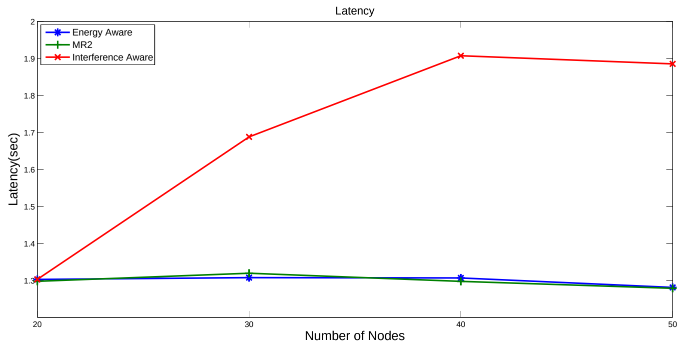


Figure 4.2: Latency

4.2.3 Average Control Packet Overhead

It is the average of the amount of energy consumed due to transmission and reception of control packets. The result is shown in Figure 4.3. The proposed protocol has 12% (approx.) less control packet overhead in comparison to MR2 and LIEMRO

4.2.4 Average Energy Consumption

It is the average of amount of energy consumed due to transmission and reception of control and data packets. The result is shown in Figure 4.4. The proposed scheme Energy Aware Multipath Routing 5% less average energy consumption in comparison to MR2 and 28% less average energy consumption in comparison to LIEMRO.

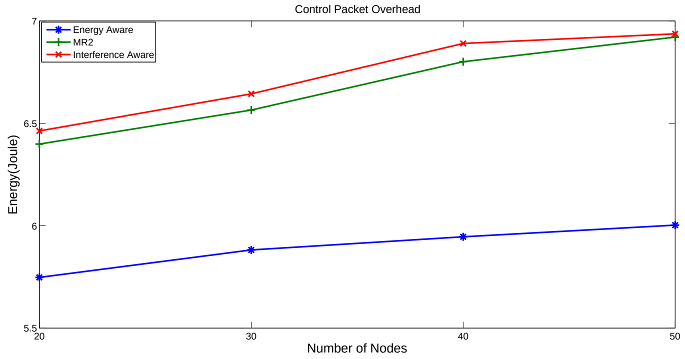


Figure 4.3: Control Packet Overhead

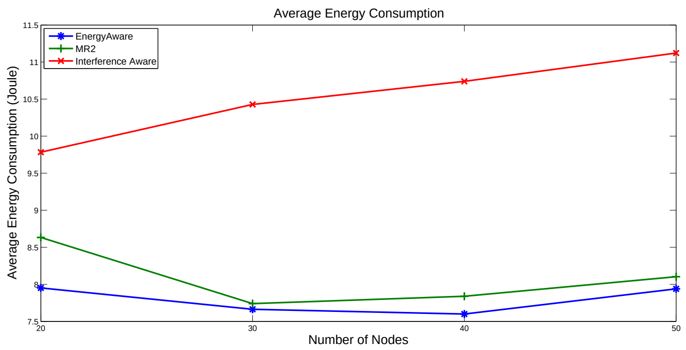


Figure 4.4: Average Energy Consumption

Chapter 5

Conclusion

5.1 Conclusion

In this thesis, we proposed an energy efficient multipath routing protocol for WSN. This protocol is designed to decrease the routing overhead, improve the latency and packet delivery ratio and through discovering multiple paths from the source to the destination. It has a sink initiated Route Discovery process with the location information of the source known to the sink. There are two types of nodes which are used here one is primary and the other is alternate. At the end of the route formation one primary path and multiple alternate paths are built and all nodes except the primary paths nodes are put to sleep mode which helps us to save energy and generate a collision free environment, the primary path is used to transmit the data from source to the sink and if the route disrupts, the next best alternate route is used for the purpose and if no path exists between the source and destination then the route discovery algorithm calls.

The simulation result finds the latency, packet delivery ratio, average control packet over head and total energy consumed. The proposed protocol has 12% (approx.) less control packet overhead in comparison to MR2 and LIEMRO, 5% less average energy consumption in comparison to MR2 and 28% less average energy consumption in comparison to LIEMRO. Regarding latency the proposed protocol has similar result to MR2 but in comparison to LIEMRO the algorithm is 24% faster. Lastly in case of Packet Delivery Ratio the proposed protocol gives improvement of 5% (approx.) over MR2 and, 12% over LIEMRO.

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Dissemination

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