Energy Efficient Adaptive Multipath Routing for Wireless Sensor Networks

R Vidhyapriya , Dr P T Vanathi

Abstract- Routing in wireless sensor networks is a demanding task. This demand has led to a number of routing protocols which efficiently utilize the limited resources available at the sensor nodes. All these protocols typically find the minimum energy path. In this paper we take a view that, always using the minimum energy path deprives the nodes energy quickly and the time taken to determine an alternate path increases. Multipath routing schemes distribute traffic among multiple paths instead of routing all the traffic along a single path. Two key questions that arise in multipath routing are *how many paths are needed* and *how to select these paths*. Clearly, the number and the quality of the paths selected dictate the performance of a multipath routing scheme. We propose an energy efficient adaptive multipath routing technique which utilizes multiple paths between source and the sink, adaptive because they have low routing overhead. This protocol is intended to provide a reliable transmission environment with low energy consumption, by efficiently utilizing the energy availability and the received signal strength of the nodes to identify multiple routes to the destination. Simulation results show that the energy efficient adaptive multipath routing scheme achieves much higher performance than the classical routing protocols, even in the presence of high node density and overcomes simultaneous packet forwarding

Keywords: *energy-efficiency, multipath routing, routing, sensor networks,*

I. INTRODUCTION

A wireless sensor network consists of light-weight, low power, small size sensor nodes. The areas of applications of sensor networks vary from military, civil, healthcare, and environmental to commercial. Examples of application include forest fire detection, inventory control, energy management, surveillance and reconnaissance, and so on [1][2][3]. Due to low-cost of these nodes, the deployment can be in order of magnitude of thousands to million nodes. The nodes can be deployed [1]either in random fashion or a pre-engineered way. The sensor nodes perform desired measurements, process the measured data and transmit it to a base station, commonly referred to as the sink node, over a wireless channel. The base station collects data from all the nodes, and analyzes this data to draw conclusions about the activity in the area of interest [4]. Sinks also can act as gateways to other networks, a powerful data processor or access points for human interface. They are often used to disseminate control information or to extract data from the network.

Key issues like stringent energy constraint and vulnerability of sensors to dynamic environmental conditions, still remain to be addressed. They create a demand for energy-efficient and robust protocol designs with specific consideration of the unique features of sensor networks, such as data-centric naming and addressing convention, high network density and power limitation. Recently, various routing protocols have been proposed for WSNs. Most of them use a single path to transmit data. The optimal path is selected based on the metrics, such as the gradient of information, the distance to the destination, or the node residual energy level. Some other routing protocols that use multiple paths choose the network reliability as their design priority.

Multipath Routing has been used in literature to describe the class of routing mechanisms that allow multiple paths to be established between the source and the destination. Classical Multipath routing has been explored for two reasons. The first is *Load Balancing*: Traffic between the source and destination is split across multiple (partially or fully) paths. The second use of multipath routing is to increase the probability of *reliable data delivery*. In these approaches multiple copies of the data are sent along different paths allowing for resilience to failure of a certain number of paths. Multiple path routing has been extensively studied and used in all kinds of existing communication networks like the Internet, high speed networks and ATM networks based on the QoS requirements required. In connection-oriented networks, resource reservations must be made before data can be sent along a route. For short or bursty connections, a selected route must have the required resources to ensure appropriate communication with regard to desired quality-of-service (QoS). For example, in ATM networks, the route setup process considers only links with sufficient resources and reserves these resources while it advances toward the destination. The same concern for QoS routing appears in datagram networks such as the Internet, when applications with QoS requirements need to reserve resources along pinned routes. The multi-path reservation algorithms perform comparably to single-path reservation algorithms, either persistent or not, the connection-establishment time for multi-path reservation is significantly lower. Thus, multi-path reservation

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becomes an attractive alternative for interactive applications such as World Wide Web browsing. With classic shortest path routing schemes a few nodes that lie on many of these shortest paths are depleted of their energy at a much faster rate than the other nodes. As a result of these few dead nodes, the nodes in its neighborhood may become inaccessible, which in turn causes a ripple effect and the whole network to become partitioned and inoperable. In multiple path routing each source discovers and maintains a set of routes that can be used to reach its destination; the possible routes can be discovered by applying a source routing algorithm. We explore the use of multiple path routing to provide load balancing so that the lifetime of sensor network can be prolonged by spreading the traffic over a larger number of nodes. Load balancing is especially useful in energy constrained networks because the relative energy level of the nodes does affect the network lifetime more than their absolute energy level.

In our proposed routing protocol we spread the traffic over the nodes lying on different possible paths between the source and the sink, in proportion to their residual energy and received signal strength. The rationale behind traffic spreading is that for a given total energy consumption in the network, at each moment, every node should have spent the same amount of energy. The objective is to assign more loads to under-utilized paths and less load to over-committed paths so that uniform resource utilization of all available paths can be ensured. Multipath routing is cost effective for heavy load scenario, while a single path routing scheme with a lower complexity may otherwise be more desirable. We compare our proposed scheme with the directed diffusion [5] and flooding protocols Simulation results show that energy efficient adaptive multipath routing outperforms the traditional routing approaches in terms of network lifetime, load balancing and packet delivery ratio. The remainder of the paper is organized as follows. Section II provides a brief overview of the related work. Section III explains the operation of energy efficient adaptive multipath routing. Section IV provides the performance evaluation of our scheme as well as the comparisons with other protocols. Section V provides the conclusion of the work and discusses future directions

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II. RELATED WORK

Sensor networks introduce new challenges that need to be dealt with as a result of their special characteristics. Their new requirements need optimized solutions at all layers of the protocol stack in an attempt to optimize the use of their scarce resources [6] [7]. In particular, the routing problem, has received a great deal of interest from the research community with a great number of proposals being made. The proposed protocols that use multiple paths [9] [10] [11] choose the network reliability as their design priority. The authors in [12] proposed an algorithm which will route data through a path whose nodes have the largest residual energy. The path is changed whenever a better path is discovered. The primary path will be used until its energy falls below the energy of the backup path after which the backup path is used. Using this approach, the nodes in the primary path will not deplete their energy resources through continual use of the same route, hence achieving longer life. However, the path switching cost is more. The authors of [9] proposed the use of a set of sub-optimal paths occasionally to increase the lifetime of the network. These paths are chosen by means of a probability which depends on how low the energy consumption of each path is. The path with the largest residual energy when used to route data in a network may be very energy- expensive too. So, there is a tradeoff between minimizing the total power consumed and the residual energy of the network. The authors in [13] proposed an algorithm in which the residual energy of the route is relaxed a bit in order to select a more energy efficient path. In [14], multipath routing was used to enhance the reliability of WSNs. The proposed scheme is useful for delivering data in unreliable environments. It is known that network reliability can be increased by providing several paths from source to destination and by sending the same packet on each path. However, using this technique, traffic will increase significantly. Hence, there is a tradeoff between the amount of traffic and the reliability of the network. This tradeoff is studied in [15] using a redundancy function that is dependent on the multipath degree and on failing probabilities of the available paths. The idea is to split the original data packet into sub-packets and then send each sub-packet through one of the available multipaths. It has been found that even if some of these sub-packets were lost, the original message can still be reconstructed. According to their algorithm, it has also been found that for a given maximum node failure probability, using higher multipath degree than a certain optimal value will increase the total probability of failure. Directed diffusion [5] is a good candidate for robust multipath routing and delivery. Based on the directed diffusion paradigm, a multipath routing scheme that finds several partially disjoint paths is studied in [11] (alternate routes are not node disjoint, i.e., routes are partially overlapped). It has been found that the use of multipath routing provides viable alternative for energy efficient recovery from failures in WSN. The motivation of using these braided paths is to keep the cost of maintaining the multipaths low. The costs of alternate paths are comparable to the primary path because they tend to be much closer to the primary path.

In [16] and [17], multipath extensions of Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV) were proposed to improve the energy efficiency of ad hoc networks by reducing the frequency of route discovery. Directed transmission [18] is one of the probabilistic routing techniques, which are derived from the flooding. It uses a retransmission probability function to reduce redundant copies of same event data. The hop distance to the destination and the number of steps that the data packets has traveled are used as parameters. The retransmission control mechanism avoids the intensive usage of the shortest path in a certain level. The energy-aware routing is proposed in [9]. It uses localized flooding of request messages to find all possible routes between the sources and sinks, as well as the energy costs associated to these paths. In the routing table of the sensor node, every neighbor is associated with a transmission probability, which is computed based on the cost of the path passing through it. The scheme maintains multiple paths but uses only one of them at a time, in order to avoid stressing a particular path and extend the network lifetime. In [12], the multipath routing is formulated as a linear programming problem with an objective to maximize the time until the first sensor node runs out of energy. The sources are assumed to be transmitting data packets at a constant rate. In [19], the multipath routing is formulated as a constrained optimization problem by using deterministic network calculus. The data transmission relies mostly on the optimal path. The alternative path is used only when the nodes on the primary route fail. Although the existing single-path approach is flexible, simple and scalable, nodes may deplete their energy supply at a faster rate. This may result in early network partition.

III. MULTIPATH ROUTING SCHEME

The sensor nodes are distributed randomly in the sensing field. A network composed of a sink node and many wireless sensor nodes in an interesting area is considered. Assume that all nodes in the network are assigned with a unique ID and all nodes are participating in the network and forward the given data. The sensor nodes are assumed to be fixed for their lifetimes, and the identifier of sensor nodes is determined *a priori*. Additionally, these sensor nodes have limited processing power, storage and energy, while the sink nodes have powerful resources to perform any tasks or communicate with the sensor nodes. Once the nodes are deployed, they remain at their locations for sensing tasks. The sensor nodes can receive messages from other nodes. The sink node is initialized with a hop value *"0"*, while other sensor nodes are *"∞"*. The energy efficient adaptive multipath routing algorithm proposed is used for selecting the neighboring nodes, to which the data message has to be forwarded. A node is selected to forward the data based on its available energy level and signal strength. Ideally, the greater the energy in the node and farther the node from the previous one, is the more likely to be selected as the next hop. The nodes which are not selected in this process will move to the sleep state in order to conserve power. The communication is assumed to be bidirectional and symmetric. The protocol replies with multiple routes from the source node to the sink quickly, and prepares the paths that efficiently balance the energy of the nodes. It also enables the selected nodes in the path to aggregate all the received packets during a short period of time and to transmit only the aggregated packet to the upstream node. Each node maintains a neighbor table for the routing protocol to function. The neighbor table contains an entry of all the selected neighboring nodes through which a node can transmit data.

A. Multipath Routing

The multi-path routing models the sensor network into levels according to the hop distance from the sink node to a source node. A node is in level L, if it is L hops apart from the sink. The sink is a level 0 node. All nodes that can talk directly with at least one level N node but cannot talk directly with any level N-1 nodes are defined as level N+ 1 node. Thus, level N nodes have path length of N hops back to the sink. The multipath routing algorithm is composed of two phases: Multipath Construction Phase and Data Transmission Phase by using two messages namely route request message and route reply message. Route Request message is transmitted when a node enters in the network to execute the neighbor discovery process during the network startup and also to establish a route to the destination and Route Reply message is initiated when the given source node is reached and to create a new entry in the local neighbor table.

B. Multipath Construction Phase

The sink node starts the multipath path construction phase to create a set of neighbors that is the address of all nodes that are able to transmit data from the source. During this process route request messages are exchanged between the nodes. Each sensor node broadcast the route request packet once and maintains its own routing table. When sensor node disseminates a data packet, it only needs to know its neighboring node to transfer, don't need to maintain the whole path information. Since the paths are formed whenever it is required unlike proactive routing protocols where it is necessary to store the routing information, it reduces the overhead of sensor node. Although the multipath routing protocol has to compute some information to record in the routing table of sensor node, the energy expense is less than transmit and receive. Furthermore, it supports multipath data forwarding, not using the fixed path. So the energy consumption will be distributed and the lifetime of network is prolonged.

The format of route request message is shown in Fig. 1. The *Source ID* contains the node ID of the message destination; *SeqNumber* field is a packet sequence. The *HopCount* field is the number of hops from the sink node which is used to identify nodes in different levels, nodes that can receive the radio signal of sink are defined as one-hop / level 1 nodes, *Energy threshold* field provides the minimum required energy level for a node to be selected for data transmission, *Signal Strength threshold* to indicate the minimum distance the node has to be located in order to receive all the data's transmitted to that node and *Sink ID* indicates the ID of the sink which broadcasts the route request packet.

Source ID	SeqNumber	HopCount	Energy Threshold	SignalStrength Threshold	Sink ID

Fig 1: Route Request Message frame format

The major activities in this phase are routing path formation for each node and neighbor table creation. The sink node broadcasts the route request packet to discover the one hop nodes / level 1 nodes, the nodes which are receiving them first. Route Request messages are used to identify nodes in different levels. After a route request message is sent by sink node, the hop count records how many hops it has traveled from the sink. The hop count field is increased by one each time when a node receives the route request message. When receiving a route request, a node considers itself in level N if the hop count is N. If a smaller hop count (say, N-1) is received later from a route request with the same sequence number, as the current remembered, the node updates its level according to the new hop count. Smaller hop count nodes constantly use less energy than others.

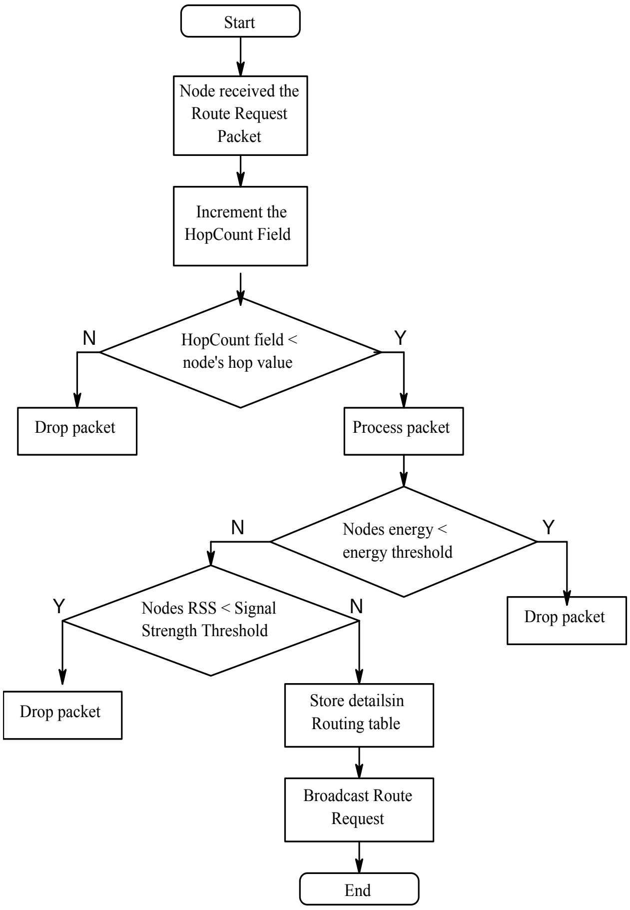

Fig 2: Multipath Construction Phase

The action flow diagram when the node receives the route request packet is as shown in Figure 2. After the *HopCount* field is incremented it is compared with the nodes hop value. If *HopCount* field is smaller than node's hop value, route request message is processed or otherwise drops the message. The corresponding node is then responsible to rebroadcast the route request message to its neighbors. The nodes which process the route request message are liable to form a path to the destination (i.e.) source. Unlike other energy-aware routing protocols, which attempt to find minimum-energy-cost paths [9] [20], this protocol provides energy-sufficient paths instead. A special flooding mechanism is adopted in the routing path formation. When an intermediate node receives the route request message, it does not forward the message to its neighbors immediately. Before sending the message out, several things are done. The intermediate node first checks the hop value if it is found to be lesser, it starts checking nodes available energy. If the available energy is less than operation energy (e.g., twice the packet transmission energy), that indicates that the node has no more energy to take more transmission jobs, the node simply discards the received request. If the node has sufficient energy, then the node measures the strength of the received signal (RSS) which is the strength of the route request message. This received signal strength measurement is indicated by the nodes Radio Signal Strength Indicator (RSSI) value. RSS is based on the principal that a radio signal between a sender and a receiver attenuates with an increase in distance. Bahl et al. [21] suggest the use of average received signal strength to estimate distances. In general, the farther the receiving node is from the sending node, the weaker the signal is. This is true for large-scale wireless propagation models such as the free space and two ray models [9]. In small-scale propagation models such as the Rayleigh model [9] and in practice [20], the signal strength may vary dramatically at the given radius for different directions because of obstacles. However, even in these cases, the weakening of the signal along the specific direction as the distance increases still holds. This protocol does not intend to precisely select the farthest node every time, but to choose nodes that are highly likely to be far away from the sender. Overall, this creates a more efficient flooding algorithm (reducing the number of retransmissions). In our simulations the signal strength threshold is fixed to be -80 dBm, since this value provides a good packet reception rate (PRR) around 85%, but for signal strength threshold values less than -85 dBm the PRR varies rather radically. It is important to note that -85 dBm is very close to the sensitivity threshold of CC2420 which is about -90 dBm.

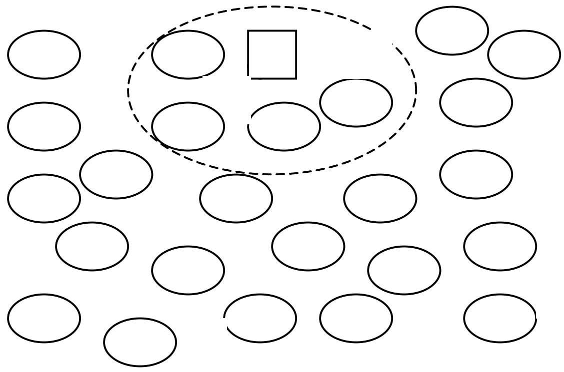

Fig 3: Sensor Network Environment

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In the figure 3 shown initially the sink node marked "S" is with a hop count of "0" and all other nodes are with a hop count of "∞", the sink node broadcasts the route request message which is received by all the nodes within the radio range of "S". The nodes after reception of the message increments the hop count field to "1" and compares with its own hop value which is "∞", if the nodes hop value is found to be a lesser value, the node processes the message further i.e., it starts to check the residual energy and the received signal strength or if the hop value is greater drops the message. When the sink initially broadcast the message, the nodes 1, 2, 3 and 4 receive the route request message. Assume that the available energy at 2 and 3 are larger than at 1 and 4, and also 2 and 3 are within the required signal strength threshold, hence nodes 2 and 3 are selected to broadcasts the route request message to their neighboring nodes. Node 5 which receives the route request packet from both node 2 and node 3 increments and verifies the hop value which is found to be lesser, since it satisfies both the available energy level and RSSI level, it accepts two paths from both node 2 and node 3. In order to route packets to node 5 we have two paths S-A-5 and S-3-5, which can be selected on demand. The path construction phase continues till the destination is reached. Using the above mechanisms, multiple paths to the destination is built utilizing some energy-sufficient nodes. An energy-sufficient node is the naturally selected node among the sender's neighbors and is usually the one with the largest available energy. The remaining nodes which are not selected in this process move to sleep state in order to conserve power. The destination node, upon receiving a new route request message, will reply with a route reply message. The header of this packet contains the same fields as those of the request packet, as well as an expected hop count field indicating the expected number of hops needed for the packet to travel to reach the target node (in this case, the sink). Unlike the broadcast message, the route reply packet does not rely on flooding to find its return path back to the source; it just uses the nodes through which it received the broadcast message.

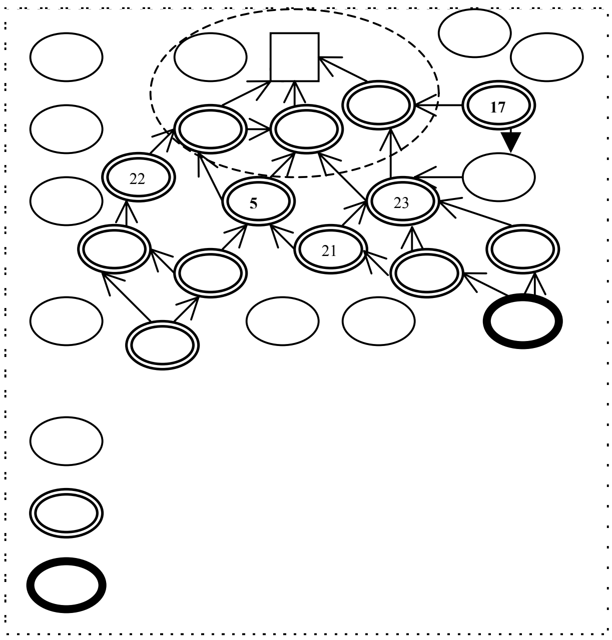

Fig 4: Path Constructed Environment

As shown in figure 4, consider node 20 is the destination node (source), when it receives a route request message it compares the *Source ID* field from the request message with its own ID, since both are found to be the same it reply's back with the route reply message. The route reply message passes through the paths through which the node received the route request and creates an entry in the neighbor table of each node.

After establishing the paths between the network nodes, the paths are stored in a routing table as shown in Table 1 to allow future queries. These routing tables are formed in the nodes which are having required energy level and required received signal strength threshold. The routing tables are used to store information about the multiple paths that can be used to direct data messages and verify the validity of each table record. The next hop address field in the routing table shown consists of address of all the nodes which can be used to route packets to the sink.

Table 1 Routing Table

Fields	Description
Destination	Destination Address
Sequence Number	Sequence number of the previous message
Next Hop	Next node address
Hop Count	Hop Count to destination
Lifetime	Validity of the route

C. Data Transmission Phase

After multiple paths are discovered, the source node begins to transmit data packets with the assigned rates on each path. The DATA message carries the event data and other control fields [22]. At the sink, it updates the path in its routing table each time a DATA message arrives. The packet format is as follows: *<Seq_Number, Source ID, Sink ID, Data_Len, Payload>*. The *Seq_Number* field is a sequence number of the packet. The *Source ID* and *Sink ID* fields respectively are the source node of the packet, and the sink node that requests the data packet. The *Data_Len* field denotes the packet length, and the *Payload* field is used to carry the data. The updated values help the sink node to monitor the conditions of the multiple paths being used. The initial data rate assignments for the paths may not be optimal for the duration of the connection. The sink node has to re-distribute the data rates over paths to optimize the usage of network resources occasionally. In order to detect a path failure, the sink also monitors the inter-arrival delay of data packets on each path. When the delay is above a pre-determined threshold, the sink presumes that the path is broken. If the number of current working paths is equal to or lower than two, the sink will send a RESET message to the source through the optimal path to indicate that sink starts to re-initiate the paths search phase. Otherwise, the sink readjusts the data rate allocation over other functional routes (i.e.) sensor node uses different path every time to extend the lifetime of network system based on the information available in the routing table. This mechanism can avoid the path search phase being invoked frequently. Data is cached in the sender until an ACK is received from the receiver. If no ACK is received within a timeout period, an error report is generated and the data will be sent back to the original source of this data in order to retransmit

For example, in Figure 4, node 20 which is the source node has two paths 15 and 19. Node 20 first disseminates data packets to node 19. If node 19 replies with an ACK packet, then node 20 updates the neighbor table. Conversely, if node 19 does not reply with a *ACK* packet, it is removed from neighbor table, since its energy may run out, or the path may be broken and so the data packet cannot be transferred via this node. Each node performs the same motion as node 20 until the data packet reaches the sink node. Further data packets from the same source can be forwarded to the sink via many paths. The lifetime of the network can be extended if the sensor node always uses a different path to send data packets.

D. Data Aggregation

In order to save more energy of whole network, we also add the *data aggregation* mechanism into multipath routing. All nodes will aggregate data except the node that sensed the event (source node) and generated the data. When a node receives data packets from its different lower level nodes, it will rearrange the packet(s) by the *Sink ID* field of packet. After that, node aggregates the packet(s) by merging their Payload field and modifying other fields. Hence, nodes do not need to execute many computing actions for data aggregation. Finally, only one data packet is transferred to the sink node.

IV. PERFORMANCE ANALYSIS

We simulate energy efficient adaptive multipath routing on GloMoSim [23], a scalable discrete-event simulator developed by UCLA. This software provides a high fidelity simulation for wireless communication with detailed propagation, radio and MAC layers. We compare energy efficient routing with two popular sensor networks routing protocols – directed diffusion and flooding the bench mark scheme.

A. Simulation Model

The GloMoSim library [23] is used for protocol development in sensor networks. The library is a scalable simulation environment for wireless network systems using the parallel discrete event simulation language PARSEC. The distributed coordination function (DCF) of IEEE 802.11 is used as the MAC layer in our experiments. It uses Request-To-Send (RTS) and Clear-To-Send (CTS) control packets to provide virtual carrier sensing for *unicast* data packets to overcome the well-known hidden terminal problem. Each data transmission is followed by ACK. Sensor nodes around 100 are uniformly distributed over a 1000m×1000m area. Initially, 10 Joules of energy is assigned to every node and then we inject the network with 1000 randomly generated packets. The values of parameters used for simulations are as shown in Table 2. The process is performed for various energy levels also. The source and destination of each packet are randomly chosen and the sizes of packets are drawn from a uniform distribution between 1 and 100 units. The effective radio range is 250 meters. The log-distance path loss model is used and the path loss exponent is set to 4.0. Data packets are generated at intervals of 1 second. All experiments are repeated several times with different random seeds and different random node topologies. When a packet arrives, the algorithm will be invoked to compute the paths. If the algorithm can not return a solution or the energy level of the nodes cannot satisfy the requirement imposed by the packet size, this packet will be rejected. The simulation is run for 750 seconds therefore each protocol has enough time to discover the route from the sink to the source and produce substantial amount of data traffic.

Table 2 Assumed Parameters

Parameters	Value
Transmission range	250 m
Simulation Time	> 700 s
Topology Size	1000m x 1000m
Number of sensors	100
Number of sinks	1
Traffic type	Constant bit rate
Packet rate	5 packets/s
Packet size	512 bytes
Radio range	350m
MAC layer	IEEE 802.11
Bandwidth	2Mb/s
Transmit power	660mW
Receive power	395mW
Idle power	35mW
Node Placement	Uniform
Initial energy in batteries	10 Joules
Signal Strength Threshold	-80 dbm
Energy Threshold	0.001mJ

For the evaluation of protocols the following three metrics have been chosen. Each metric is evaluated as a function of the topology size, the number of nodes deployed, and the data load of the network.

B. Performance Metrics

Node Energy Consumption **(E_a):** The *node energy consumption* measures the average energy dissipated by the node in order to transmit a data packet from the source to the sink. The same metric is used in [5] to determine the energy efficiency level of WSNs. It is calculated as follows:

$$E_a = \frac{\sum_{i=1}^{M}(e_{i,init} - e_{i,res})}{M\sum_{j=1}^{S} dataN_j}$$

where M is the number of nodes, $e_{i,init}$ and $e_{i,res}$ are respectively the initial and residual energy levels of node i, S is the number of sink nodes and $dataN_j$ is the number of data packets received by sink j.

Data Delivery Ratio (R): This metric represents the ratio between the number of data packets that are sent by the source and the number of data packets that are received by the sink.

$$\text{Data Delivery Ratio} = \frac{\text{Successfully delivered data}}{\text{Required data}}$$

This metric indicates both the loss ratio of the routing protocol and the effort required to receive data. In the ideal scenario the ratio should be equal to 1. If the ratio falls significantly below the ideal ratio, then it could be an indication of some faults in the protocol design. However, if the ratio is higher than the ideal ratio, then it is an indication that the sink receives a data packet more than once. It is not desirable because reception of duplicate packets consumes the network's valuable resources. The relative number of duplicates received by the sink is also important because based on that number the sink, can possibly take an appropriate action to reduce the redundancy

Average Delay: It is defined as the average time between the moment a data packet is sent by a data source and the moment the sink receives the data packet. This metric defines the freshness of data packets.

C. Simulation Results

Under energy constraints, it is vital for sensor nodes to minimize energy consumption in radio communication. From the results shown in Fig 5, It is observed that there is a lower node energy consumption of our adaptive multipath routing over the other schemes. The flooding is the most costly protocol because the number of hops tends to increase as the node density increases. The directed diffusion obtains further improvement. Figure 5 shows a linear energy increase as the network becomes denser, as more sensor nodes get involved with for both directed diffusion and multipath algorithm.

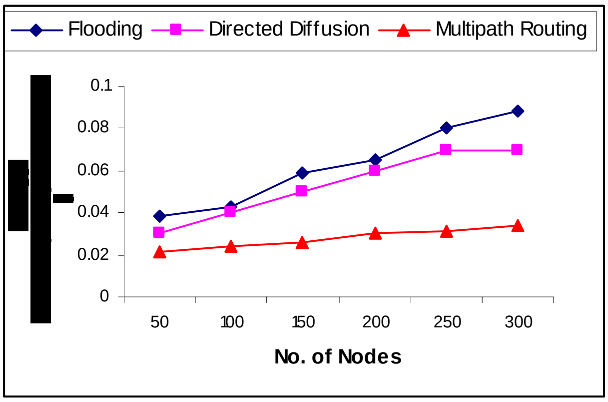

Fig 5: Average Node Energy Consumption

The reason that the energy consumption of directed diffusion algorithm increases faster than multipath routing algorithm is because the number of sensors participating in the route discovery is less. The improvement of multipath routing is ranging from 10% to 30% when compared with directed diffusion. Such 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.

Figure 5 shows the *delivery ratio* of all the three routing protocols. To eliminate packet loss we use a rate of 5 packets / second. It is found that the delivery ratio of all the protocols increase as the node density increases. When node density is high, there are more nodes available for data forwarding, and this increases the delivery ratio. Flooding offers less packet delivery rates, followed by flooding is directed diffusion; it did not adapt well its behavior to network size increase. The energy efficient multipath routing protocol has maintained constant delivery rates throughout the simulated scenarios because the paths are selected based on the energy availability.

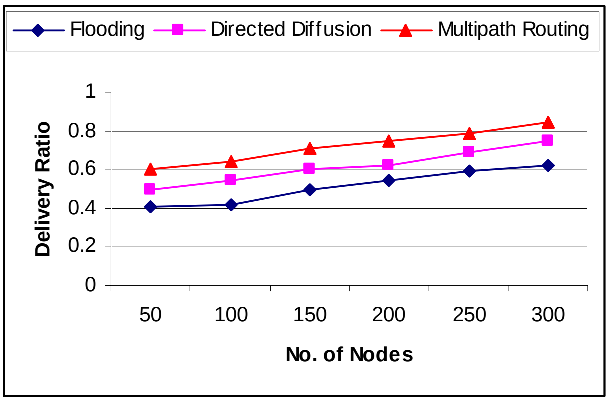

Fig 6: Delivery Ratio

This is a result of the impact of the process it uses to create a routing path. Under energy constraints, it is vital for sensor nodes to minimize energy consumption in radio communication to extend the lifetime of sensor networks. From the results shown in Figure 6, we infer that energy efficient multipath routing tends to reduce the number of hops in the route, thus reducing the energy consumed for transmission.

Figure 7 demonstrates the *load balancing* capability of three routing schemes. Average forwarded data is measured as the average number of data events relayed by a data forwarder for every distinct event delivered to sinks

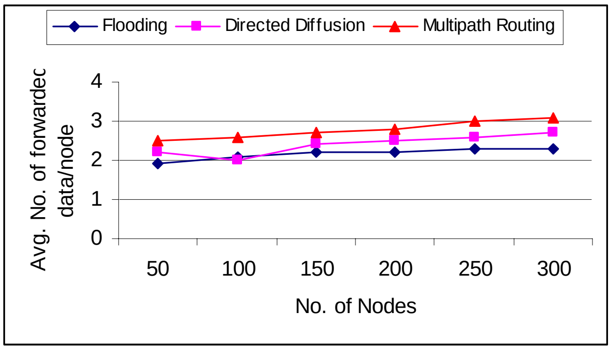

Fig 7: Load Balancing Capability

This metric reflects the long-term energy efficiency and potential network fault tolerance. As shown in Figure 7, load balancing capacity of multipath routing increases twice than other routing protocols in most of the density scenarios.

We also study the *end-to-end delay* performance of these routing protocols. Both route availability delay and propagation delay of data packets contribute to the data latency. The average packet delays under the three schemes are plotted in Figure 8. Additional delay is no more than approximately 1.3 seconds for the 250m transmission ranges. This additional delay grows slowly with the increase of node population. Overall, these results show energy efficient multipath routing protocol's ability to sustain application performance even for large node densities. Many other attempts at energy savings showed that packet delivery performance usually decreases as a result of increased energy savings. Our results show that energy efficient algorithm can decrease the energy expense of communication with minimum tradeoffs in quality of service. For all traffic conditions multipath routing exhibits less than two-third the data latency of flooding, this is due to the fact that the route selection is more optimized by choosing shortest multipaths against the longer paths.

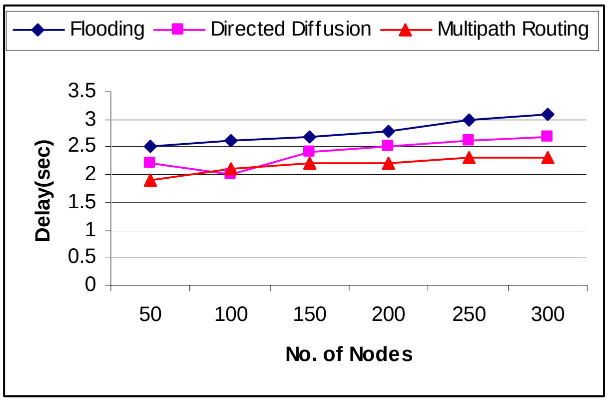

Fig 8: Average Data Packet Delivery Delay

V. CONCLUSION

Energy resource limitations are of priority concern in sensor networks. Distributing the load to the nodes significantly impacts the system lifetime. The adaptive multipath routing protocol is capable to search multiple paths and aims to allocate the traffic rate to each path optimally. Simulation results show that our proposed scheme has higher node energy efficiency, than the directed diffusion, and flooding. The limitation in our scheme is the RSSI values which are used, are not constant throughout the simulation period, moreover the fading and interference caused by wireless environments are not taken into consideration this poses a limitation on identifying the network performance in real world scenario. There are several future works we would like to focus on. First, how to guarantee the delivery of packets under situations where non-uniform transmission ranges exist. Second to improve the algorithm to include the integration of data aggregation and finally the support of node with limited mobility. An optimal solution to this problem especially for mobile sensor networks is still an open question.

REFERENCES

[1] A. Mainwaring, D. Culler, J. Polastre, R. Szewczyk, and J. Anderson, "Wireless sensor networks for habitat monitoring", In *Proc. of the First ACM International Workshop on Wireless Sensor Networks and Applications (WSNA-02)*, 2002

[2] Y. Gsottberger, X. Shi, G. Stromberg, T. F. Sturm, and W. Weber, "Embedding low-cost wireless sensors into universal plug and play environments". In proc. Of *EWSN*, 2004

[3] K.A. Delin. Sensor web in Antarctica. "Developing an intelligent, autonomous platform for locating biological flourishes in cryogenic environments". In *34th Lunar and Planetary Science Conf. (LPSC 03)*. 2003

[4] F. L. LEWIS, "Wireless Sensor Networks", D.J. Cook and S.K. Das, editors, *Smart Environments: Technologies, Protocols, and Applications*, John Wiley, New York, 2004.

[5] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: A scalable and robust communication paradigm for sensor networks," in *Proc. of ACM MobiCom'00*, Boston, MA, USA, Aug. 2000, pp. 56–67

[6] Akyildiz, I., Su, W., Sankarasubramaniam, Y. e Cayirci, E. "A Survey on Sensor Networks", IEEE Communications Magazine, pp. 102-114, 2002

[7] S. Tilak, N. B. Abu-Ghazaleh and W. Heinzelman, "A Taxonomy of Wireless Micro-Sensor Network Models", Mobile Computing and Communications Review, Vol. 6, No. 2, pp. 28-36, 2002.

[8] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad-hoc routing," in *Proc. of ACM/IEEE MobiCom'01*, Rome, Italy, July 2001, pp. 70 – 84.

[9] R. Shah and J. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Proc. of IEEE WCNC'02*, Orlando, FL, March 2002, pp. 350–355.

[10] K. Wu and J. Harms, "On-demand multipath routing for ad hoc networks," in *Proc. of European Personal and Mobile CommunicationsConference (EPMCC)*, Vienna, Austria, Feb. 2001.

[11] D. Ganesan, R. Govindan, S. Shenker, and D. Estrin, "Highly-resilient, energy-efficient multipath routing in wireless sensor networks," in *Proc. of ACM MobiHoc'01*, Long Beach, CA, USA, Oct. 2001.

[12] J. Chang and L. Tassiulas, "Energy conserving routing in wireless adhoc networks," in *Proc. of IEEE INFOCOM'00*, Tel-Aviv, Israel, March 2000, pp. 22–31.

[13] Q. Li and J. Aslam and D. Rus, "Hierarchical Power-aware Routing in Sensor Networks", In Proceedings of the DIMACS Workshop on Pervasive Networking, May, 2001.

[14] S. Dulman, T. Nieberg, J. Wu, P. Havinga, "Trade-off between Traffi Overhead and Reliability in Multipath Routing for Wireless Sensor Networks", WCNC Workshop, New Orleans, Louisiana, USA, March 2003.

[15] Jian Wu, Stefan Dulman, and Paul Havinga " Reliable Splitted Multipath Routing for Wireless Sensor Networks" Proceedings of Building Intelligent Sensor Networks (BISON 04), China 2004

[16] A. Nasipuri and S. Das, "On-demand multipath routing for mobile ad hoc networks," in *Proc. of International Conference on Computer Communications and Networks (IC3N)*, Boston, MA, USA, Oct. 1999.

[17] M. Marina and S. Das, "On-demand multipath distance vector routing in ad hoc networks," in *Proc. of the Ninth International Conference for Network Protocols (ICNP)*, Riverside, CA, USA, Nov. 2001.

[18] C. Barrett, S. Eidenbenz, L. Kroc, M. Marathe, and J. Smith, "Parametric probabilistic sensor network routing," in *Proc. of ACM WSNA'03*, San Diego, CA, Sept. 2003, pp. 122–131.

[19] S. Mao, S. Panwar, and Y. Hou, “On optimal traffic partitioning for multipath transport,” in *Proc. of IEEE INFOCOM’05*, Miami, FL, March 2005, pp. 2325–2336.

[20] C. Ying, Q. Lu, Y. Liu and M. Shi, “Routing Protocols Overview and Design Issues for Self-Organized Network”, In Proc. Of *International Conference on Communication Technology (WCC – ICCT),* Volume 2, pp. 1298-1303, 2000

[21] Bahl, P., Padmanabhan, V.N. “RADAR: An In-Building RF-Based User Location and Tracking System”., In Proc. of IEEE Infocom 2000, Tel-Aviv, Israel, pp 775-784, March 2000

[22] Y. Lu, “Multipath routing algorithm for wireless sensor networks,” Master’s Thesis, University of British Columbia, Vancouver, Canada, Dec. 2005.

[23] M. Takai, L. Bajaj, R, Ahuja, R. Bagrodia and M. Gerla. “GloMoSim: A Scalable Network Simulation Environment”, *Technical report 990027*, UCLA, Computer Science Department, 1999.