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A Dynamic Fault Tolerant Routing Protocol for Prolonging the Lifetime of Wireless Sensor Networks

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Abstract — **Wireless Sensor Networks (WSNs) are being extensively used for various applications. WSNs consist of a large number of small nodes with sensing, computation, and wireless communication capabilities. Sensor nodes are typically resource deficient with energy being the most critical of all the resources. Efficient use of energy resources in sensor nodes can extend the lifetime of WSNs. The main purpose of such networks is to gather information from the environments and deliver the same to the applications. Thus routing in WSNs is a demanding task. Multihop routing is always better as it has many advantages over the single hop networks. It not only reduces the congestion but also leads to better utilization of energy resources as individual nodes can operate with low transmission power. Any routing protocol has to ensure that data can always be routed from source to sink. The work in this paper aims at designing a multilevel fault tolerant routing protocol that extends the network lifetime. It is also consistent over data transmission even when a sensor node runs out of energy; thus maintains network connectivity. In our proposed work when a sensor node runs out of energy it finds a suitable alternative path to sink node by establishing a new connection dynamically with the nodes within its range. The alternative path increases the data transmission accuracy between source nodes to its respective sink node. Simulation studies of the proposed routing protocol have been carried out using Castalia simulator, and its performance has been compared with that of flooding and directed diffusion. The simulation results show that the proposed approach has lower energy consumption and data packet delivery delay, and higher delivery ratio.**

Keywords—**Wireless Sensor Networks, multilevel routing protocol, reliable data transfer, energy efficient network connectivity.**

I. INTRODUCTION

A wireless sensor network (WSN) consists of spatially distributed autonomous devices called sources, and one or more sinks to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants at different locations. The research in sensor networks received a big boost with a number of funding initiatives by US military, NSF and DARPA SENSIT. Many novel sensor based applications have emerged in recent past. We may classify the sensor applications into following classes:

- Monitoring spaces: This class refers to passive data gathering recognizing occurrence of some events or conditions. The gathered data are typically inputs to a number of target applications. These target applications include habitat monitoring, monitoring of crops (failure, pest attack), climate control, security surveillance, intelligent alarms (fire, flash flood, volcanic eruption) etc.
- Monitoring things: This class refers to gathering data to recognize occurrence of specific states of a system. On occurrence of these states the system may execute a sequence of internal transitions to get into a desirable state. The target applications could be structural monitoring (bridge health monitoring), equipment maintenance, medical diagnostics, etc.
- Monitoring complex interactions: It involves monitoring of complex interactions of systems and things. For example, wild-life habitat monitoring, disaster management, emergency response, smart environments, surface and sea navigation, health care, manufacturing process flow, etc., would require complex interactions of systems with objects or things.

Such wide-ranging applications requiring WSNs make them candidates for intense research. The research spans hardware, systems, networking and programming methodologies. Considering ubiquity of applications, one of the crucial design decisions for sensor nodes has been to settle for a small form factor. The advantage of small form factor is that these miniature devices are inexpensive. Thousands of sensor nodes can be deployed with a low cost. Therefore, the key to success of sensor based applications is to network sensors in an efficient way for gathering sensory data from their respective deployed environments.

A network in which all the nodes have same transmission range is called a Symmetric Network. In a symmetric network if node *A* is in the transmission range of node *B*, then *B* must also be within transmission range *A*.

If the transmission ranges of nodes are configured at the network start-up time and all the nodes do not have same transmission range, then the network is considered to be an Asymmetric Network. If node *B* is in range of *A*, it is not necessary *A* is also in range of *B*.

A sensor node basically consists of four basic components; a sensing unit, a processing unit, a communication unit and a power unit. Fig. 1 shows the basic components of a sensor node Sensing unit consists of one or more sensors and an analog to digital converters (ADC). Sensors observe the physical phenomenon and generate analog signals based on the observed phenomenon. They are the actual interface to the physical world. ADCs convert the analog signals into digital signals which are then fed to the processing unit. Processing unit usually consists of a microcontroller or microprocessor with memory which

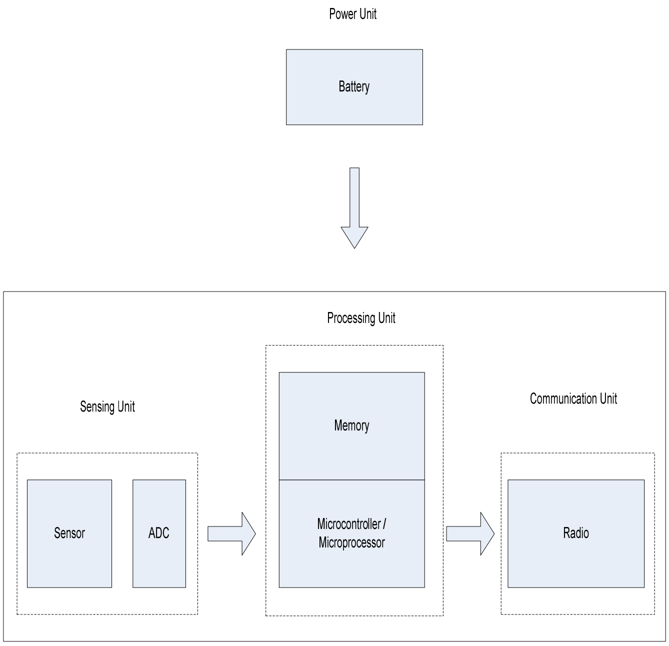

Fig 1: Basic components of a sensor node

provides intelligent control to the sensor node (example Intel's Strong ARM microprocessor and Atmel's AVR microprocessor) .Communication unit consists of a short range radio for performing data transmission and reception over a radio channel. The power unit consists of a battery for supplying power to drive all components in the system. All these units should be built into a small module with low power consumption and low production cost.

Each sensor performs two main responsibilities, namely (i) sensing activities, and (ii) routing the sensed data to the sink. The main responsibility of sink is to collect information from various sensor nodes and process it for further actions.

Routing protocols for other wireless networks like mobile ad-hoc networks or cellular networks cannot be directly applied to WSNs due to the existing design challenges in WSNs like energy consumption, node deployment, QoS, data aggregation and node mobility [1].Energy dissipation at sensor node is a major concern, as in many applications sensors have to be deployed in inaccessible environments. Sensing alone is not an energy consuming activity, but networking and programming certainly are. Prolonging battery life in sensor nodes and, by extension, the overall network lifetime is therefore a foremost task in the design of practical WSNs [2], [3], [4]. Another requirement of WSNs for applications such as tracking of intruders, detection of fire etc. is that the delay to transmit data from sensor node to the sink should be as low as possible. These are complex set of requirements which a routing protocol for wireless sensor networks needs to fulfil [5].

The design of routing protocols for WSN are influenced by many factors including hardware constraints, network topology and power consumption. The sensor networks are mainly of two types - event-driven and time-driven (or continuous dissemination networks). In the event driven networks the sensor nodes sense the data and transmit it only if the data is considered critical enough to be communicated. In the time driven networks sensors sense the data and transmit it to the central controller periodically. The periodicity of relaying data packets is application dependent.

The coverage area of a sensor node (or the approachability of a node) depends on its transmission range. If the transmission range of all the nodes is high enough to reach the sink, then it is considered one hop network. Such networks do not incur overhead of additional control packets for route discovery and maintenance. However, as the wireless is a shared medium, one hop networks lead to densely connected networks and suffer from severe congestion. In other words, there is a trade off in selecting a suitable transmission range for the nodes and severity of congestion. The range should be chosen optimally to eliminate congestion and to retain desired network connectivity.

In this paper we propose a multilevel routing protocol for event-driven WSNs that ensure reliable data transfer and withstand node failure so that no data is lost and network connectivity is maintained.

The rest of the paper is organized as follows. In section II, we give a survey of related works, and motivation for our work. The details of the proposed routing protocol are described in section III. Result of the performance evaluation of the proposed routing protocol, flooding and directed diffusion routing protocol and their comparisons are given in section IV. Section V concludes the paper with future work.

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 [8], [16], [17] choose network reliability as their design priority. The authors in [9] 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 [8] 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 trade off between minimizing the total power consumed and the residual energy of the network. The authors in [10] 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 [11], 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 trade-off between the amount of traffic and the reliability of the network. Directed diffusion [12] is a good candidate for robust multipath routing and delivery. Directed diffusion concentrated on reducing the number of multiple paths along which data traverses. It also incorporates some novel features - data-centric dissemination, reinforcement based adaptation to the best path, in-network data aggregation, and caching. A central controller called Sink injects its interest in the network by normal flooding with a large update interval. Sensors report data if they match with the interest received from the sink node. A sensor sends to the interested node through multiple paths. The neighbouring nodes establish a gradient towards each other based on the direction from which they have received interest. This way the interested data finds its path to the sink. Apart from being unsuitable for continuous data delivery, it incurs extra overhead for data matching and interest injection. Thus most multipath routing incurs an additional cost of finding and maintaining multiple routes.

III. PROPOSED WORK

The objective of the proposed multi level routing protocol is to maintain network connectivity even if a node runs out of energy, thus prolong the network lifetime and provide reliable data delivery. Besides, the applications running in the WSN are event-driven and require that the information gathered by the sensor nodes have to be transmitted immediately to the sink. The sensor nodes are distributed randomly in the sensing field. Furthermore, it is also assumed that each node has a unique *ID*, and the communication between neighbouring nodes is symmetric and bidirectional. It is also assumed that all nodes are participating in the network and forward the given data. 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.

The protocol performs three basic operations:

1. Level implementation and path establishment
2. Data Transmission
3. Withstand node failure and path reestablishment

A. Level Implementation and Path Establishment

The multi-level routing protocol 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 nodes. Thus, level N nodes have path length of N hops back to the sink.

Each node stores its node id (N_j), level (HC_j), parent node (P_j), an array (A_j) to store data packets till an acknowledgement for it is received. The sink is initialised with HC= 0, P=sink, while other sensor nodes with $HC_j=\infty$, $P_j=-1$.

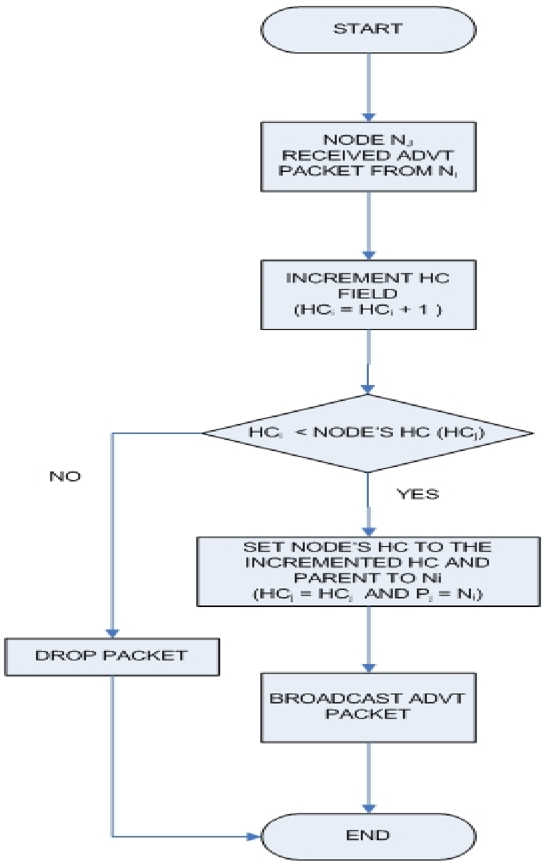

Fig 2: Flow diagram when a node receives ADVT packet

Once the nodes are deployed the sink broadcasts the ADVT packet to discover the level 1 node and set its parent to sink. After an ADVT message is sent by sink node the hop count records how many hops it has travelled from the sink. The hop count (HC) is increased by one each time when a node receives the ADVT message. When receiving an ADVT message a node considers itself in level N+1 if the hop count received is N. If a smaller hop count ADVT message is received the node updates its level according to the new hop count. The parameters of ADVT message are N_j, HC_j. Thus the ADVT message is used to model the network into levels and implement a path from each sensor node to the sink. Fig. 2 shows the action flow diagram when a node receives the ADVT packet.

In Fig. 3, node 3 which is the sink node has a HC value of 0 (i.e. Level 0), and all other nodes initially are with a HC of ∞. Node 3 broadcasts the ADVT message which is received by nodes that are within the radio range of 3. Here nodes 7, 2, 10, 16, 26, 29 receive the message from sink. On receiving the ADVT message these nodes increment the HC value received by 1 and compares this with its own HC value. If the node's HC value is less it rebroadcasts the message with its own HC value, else if the other value is smaller it updates its HC to the incremented value. And in either case sets the sender of the message as its parent node, P. If the incremented value is greater it just drops the packet. HC value denotes the level of each node. So the HC value of these nodes is set to 1 (Level 1) and sink becomes the parent node. Thus there is a one-hop path from these nodes to the sink. They then rebroadcast the message and this continues until all nodes are assigned levels subject to the condition that minimum number of hops is required to reach the sink node.

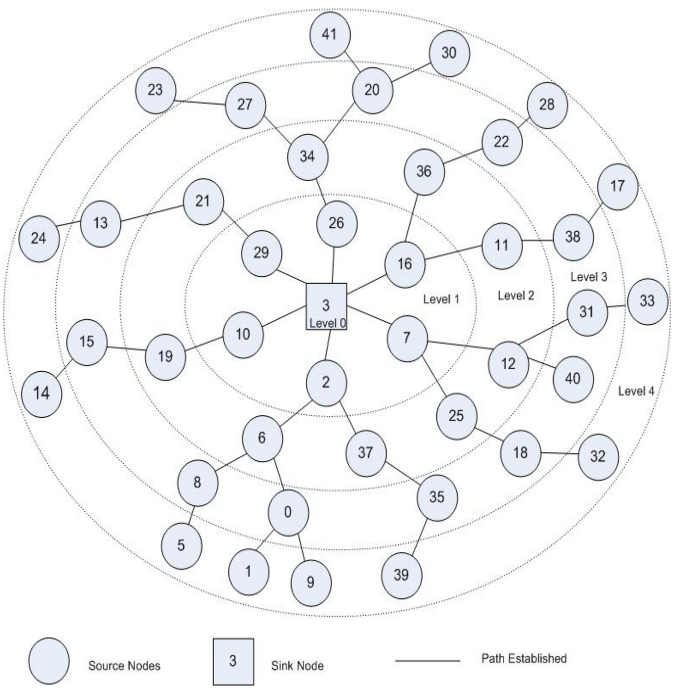

Fig 3: Level and path established

B. Data Transmission

Once level implementation is over, when an event occurs at the source node the data is forwarded from source node to parent node. The source node also stores a copy of it. Each parent on receiving a data packet sends an acknowledgement (ACK packet) to the node that forwarded the packet to it. On receiving an ACK packet it deletes the packet for which acknowledgement is received. This continues until the sink receives the packet. On receiving a sensed data item the sink needs to send an acknowledgement to the last sender. A timer is set for each data packet forwarded, to ensure reliability and no loss of data packet. Even if a data packet is lost we need not go back to the original source node to access the data. The same can be acceded by accessing the last node that forwarded the packet.

For example in fig. 3 consider an event occurs at node 8, so it needs to send the data to the sink. The data will be forwarded to the parent node (P) 6. Before sending it will also store a copy of it in its array (A). Node 6 on receiving the data packet will store a copy of it in its array and send an acknowledgement (ACK) packet to node 8. It then forwards the data packet to node 2. Same process is repeated at node 2. Finally the sink node 3 receives the data packet and sends an acknowledgement to node 2. Thus the data packet is received successfully by the sink node.

C. Withstand Node Failure and Path Reestablishment

If a node runs out of energy it uses EnergyLow packet to notify its child nodes to change their parents to ensure no disconnection occurs and thus maintain connectivity. The parameter of EnergyLow message is its ID (N_j). Nodes that receive this message and have their parent set to the node that sent the message; use Hello packets to find out new parent or their neighbours. The neighbours reply to this packet using Neighbour message whose parameters are N_j, HC_j. The nodes that change their levels due to EnergyLow message use LevelChange message to change the level of their child nodes. Parameters of LevelChange message are N_j, HC_j.

In fig. 4, if node 0 is about to run out of energy it sends an EnergyLow message to its child nodes 1 and 9. On receiving the EnergyLow message, the nodes 1 and 9 send Hello packet to find new parent. Node 8 replies to node 1 with a Neighbour message. Node 1 on receiving the Neighbour message sets Node 8 as its parent. Since its HC value has not changed it does not need to broadcast a LevelChange packet. Similarly node 39 replies to node 9 with a Neighbour message, and node 9 sets node 39 as its parent node. Here since node 9's HC value is changed to 5 (level 5 node) it needs to broadcast a LevelChange packet but since it has no child nodes it is not required.

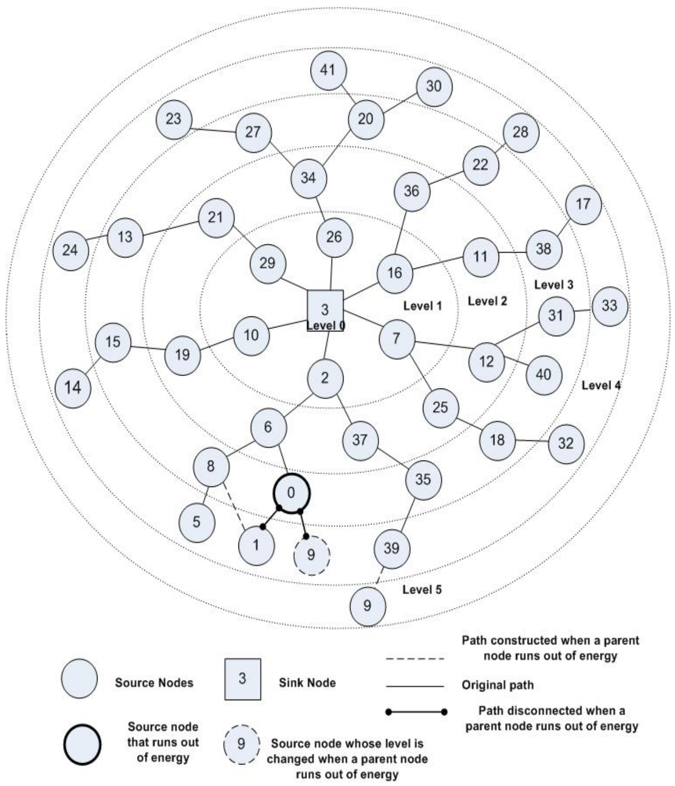

Fig 4: Reestablishment of path when a parent node runs out of energy

D. Proposed Algorithm

ALGORITHM EXECUTED AT EACH SENSOR NODE N_j ON RECEIVING A PACKET FROM NODE N_i

Phase 1: Level Implementation

/*On receiving ADVT packet*/

if ADVT packet **then**
if ($HC_j==\infty$) **then**
$HC_j=HC_i+1$;
$P_j=N_i$;
Broadcast ADVT (N_j,HC_j);
else if((P_j not sink) and ($HC_j>HC_i+1$)) **then**
$HC_j=HC_i+1$;
$P_j=N_i$;
Broadcast ADVT (N_j,HC_j);
else
Discard the ADVT;
end if
end if

Phase 2: Data Transmission

/*On receiving data packet*/

if data packet **then**
Put data packet in array A_j;
Forward data packet to parent node P_j;
Set the timer;
Send ack packet to N_i;
end if

/*On receiving ack packet*/

if ack packet **then**
Delete the packet from array A_j for which ack has been received;
end if

/*On Timer timeout */

if Timeout **then**
if (any data packet in the array) **then**
Retransmit it;
Set the Timer;
end if
end if

Phase 3: Withstand Node Failure and Path Reestablishment

/*On receiving EnergyLow packet*/

if EnergyLow **then**
if ($P_j==N_i$) **then**
$P_i = \infty$;
Broadcast hello packet;
else
Discard EnergyLow packet;
end if
end if

/*On receiving hello packet*/

if hello packet **then**
Broadcast Neighbour (N_j,HC_j);
end if

/*On receiving LevelChange packet*/

if LevelChange **then**
if ($P_j==N_i$) **then**
$HC_j=HC_i+1$;
Broadcast LevelChange(N_j,HC_j,CF_j) ;
else
Discard LevelChange packet;
end if
end if

/* On receiving neighbour packet */

if Neighbour **then**
if ($P_j==\infty$) **then**
if ($HC_i==HC_j-1$) **then**

P_j=N_i;
else if(HC_i==HC_j) **then**
P_j=N_i;
HC_j=HC_i+1;
Broadcast LevelChange(N_j,HC_j) packet;
else
P_j=N_i;
HC_j=HC_i+1;
Broadcast LevelChange(N_j,HC_j) packet;
end if
else
Discard the Neighbour packet;
end if
end if

ALGORITHM EXECUTED AT SINK NODE

Phase 1: Level Implementation

/*On Node_start_up*/

if Node_start_up **then**
Broadcast ADVT (N_i,HC_i);
end if

Phase 2: Data Transmission

/* On receiving a data packet from node Ni*/

if data packet **then**
Send ack packet to N_i;
end if

Phase 3: Withstand Node Failure and Path Reestablishment

/*On receiving hello packet*/

if hello packet **then**
Broadcast Neighbour (N_j,HC_j);
end if

IV. PERFORMANCE ANALYSIS

Simulation studies of the proposed protocol are carried out to evaluate its performance, and compared its performance with that of flooding and directed diffusion. We describe the simulation model, and the results obtained using Castalia simulator 1.3 [13].

A. Simulation Model

In our simulation, we have varied the number of nodes from 100 to 500, which are randomly deployed in different parts of deployment area with a fixed density. For this simulation, the network parameters, such as transmission range, transmission rate, sensitivity, transmission power etc., are similar to the parameters specified in CC2420 data sheet [14] and TelosB data sheet [15].The input data is generated randomly in every 1 second duration at the node where the event occurs. We have taken the initial energy of each node to be 29160 joules for 2AA batteries as given in the Castalia simulator. The simulation is run for 2400 seconds therefore each protocol has enough time to discover the route from the sink to the source and produce substantial amount of data traffic.

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 [12] 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 *dataNj* 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.

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

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

Pertinently it is necessary for sensor nodes to minimize energy consumption in radio communication. From the results shown in Fig. 5, it is found that there is a lower node energy consumption of our 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. The reason that the energy consumption of directed diffusion algorithm

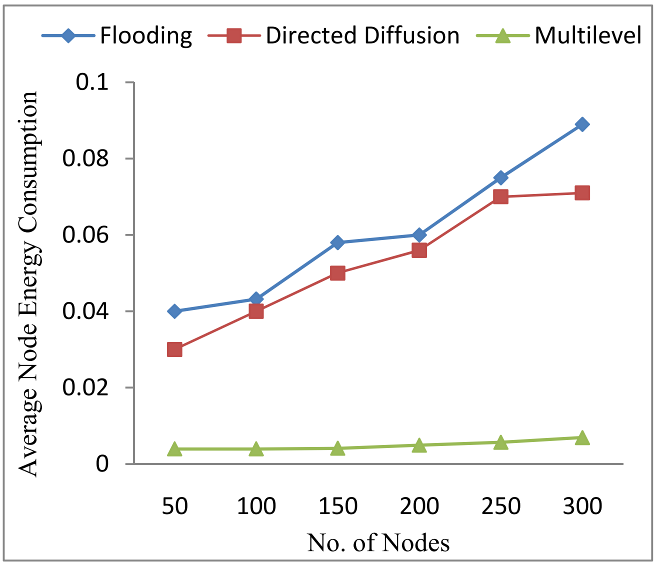

Fig. 5: Average energy node consumption

increases faster than our routing algorithm is because the number of sensors participating in the route discovery is less. The experimental results manifest that the energy efficiency of multilevel 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.

Fig. 6 shows the delivery ratio of all the three routing protocols. 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 behaviour to network size increase. The multilevel routing protocol has maintained constant delivery rates throughout the simulated scenarios. 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 Fig. 5, we understand that multilevel routing tends to reduce the number of hops in the route, thus reducing the energy consumed for transmission.

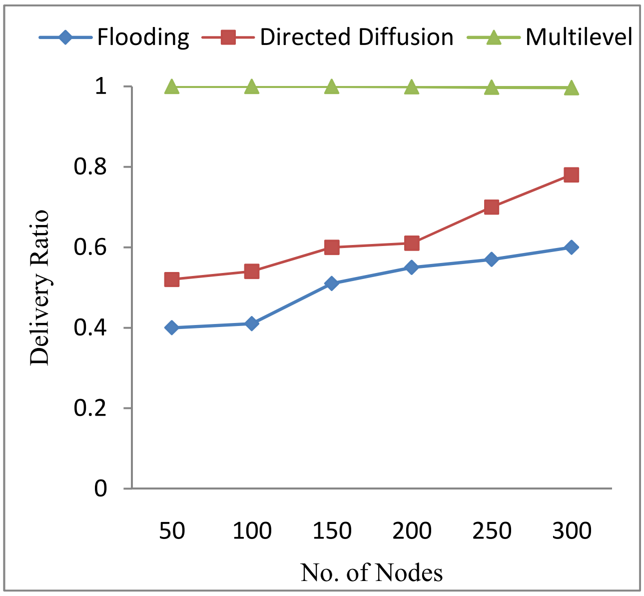

Fig. 6: Delivery ratio

Fig. 7 shows the average data packet delivery delay for each level node in a fixed area with fixed number of nodes using multilevel scheme. As the level increases, the delay also increases. But since our protocol tries to minimize the number of levels so the delay is also reduced as compared to other multihop protocols..

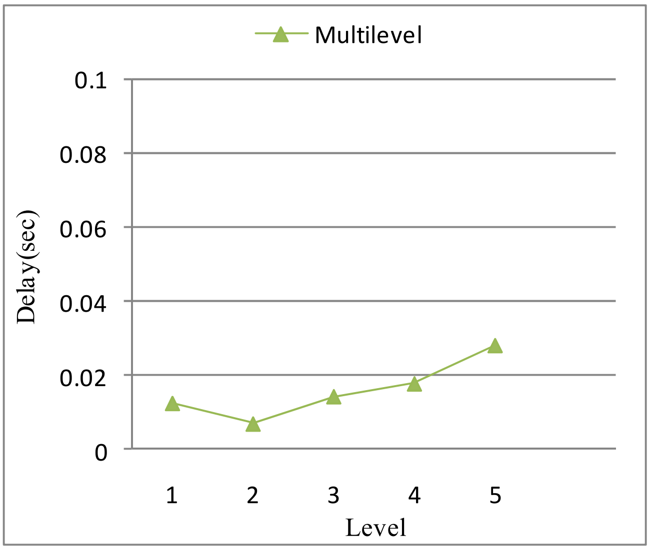

Fig. 7: Average data packet delivery delay for each level node

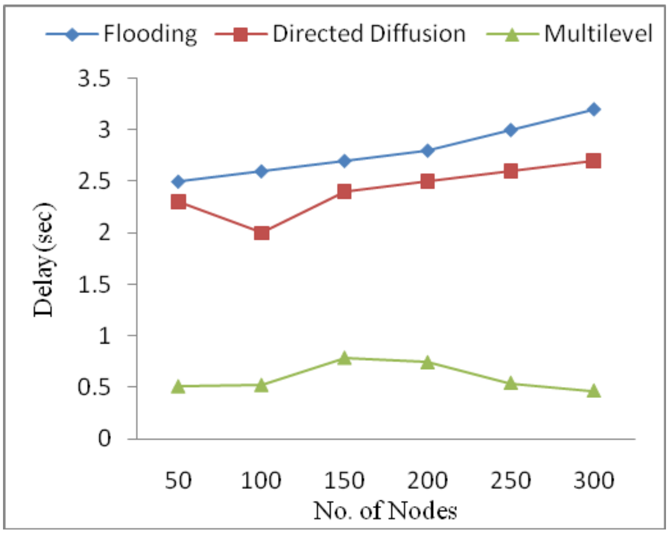

Fig. 8: Average Data Packet Delivery Delay for level 2 nodes

We also study the end-to-end delay performance of these three routing protocols. Both route availability delay and propagation delay of data packets contribute to the data latency. In fig 8 the average packet delay to transmit 1000 packets under the three schemes are plotted. Additional delay is no more than approximately 0.74 seconds for level 2 nodes. This additional delay grows slowly with the increase of node failure but remains approximately constant with increase of node population. In our simulation the delay to find an alternative path for a single node failure is 0.014346. Overall, these results show multilevel routing protocol's ability to sustain application performance even for large node densities.

V. CONCLUSION AND FUTURE WORK

Thus we have proposed a multilevel routing protocol that can withstand node failure. It maintains the connectivity of the network and the reliability of data transfer even when a node in the network runs out of energy. As stated earlier, the major constraint in sensor networks is energy resource limitations which we overcome through this proposed new protocol to some extent and thus extend the network lifetime. Simulation results reflect that our proposed scheme has higher node energy efficiency than the directed diffusion and flooding. The limitation in our scheme is that the time taken to find a new neighbour node affects the delivery of data packet, moreover the fading and interference caused by wireless environments are not taken into consideration which poses a limitation on identifying the network performance in real world scenario. We would like to focus on the following future works:

i) To guarantee the delivery of packets under situations where non-uniform transmission ranges exist (i.e. in asymmetric networks).
ii) To improve the algorithm to include the integration of data aggregation
iii) And finally the support of node with limited mobility.

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