Abstract—Routing presents a significant design challenge to meet various application requirements in wireless sensor networks (WSNs) communication. In this paper, we propose a minimum-delay multipath routing protocol with modification to dynamic source routing (DSR) protocol, which aims to minimize end-to-end delay to provide quality of service (QoS) support for delay-sensitive applications in WSNs. The proposed work takes into account, end-to-end delay and unreliability of wireless channel links to derive a routing metric used by the routing protocol to determine the cost associated with individual routes. Each node records multiple disjoint routes to the same destination, in which primary route selection is based on the derived routing metric to give preference to a route with minimum end-to-end delay for packet transmissions. Simulation results reveal better performance for the modified DSR protocol, most importantly when used for routing in unreliable wireless channel link conditions with high packet error rates.

Index Terms—channel reliability, end-to-end delay, routing protocols, wireless sensor networks (WSNs).

I. INTRODUCTION

Wireless sensor networks (WSNs) are special types of networks driven by advances in microelectromechanical system (MEMS) and proliferation of various suitable network applications in both civilian and military domains. The distributed and decentralized nature of WSNs, together with operation without infrastructure support and administration evoked a considerable research work and effort to improve their operation. It follows therefore that protocols for WSNs should be designed to be self-organizing and self-configuring. Moreover, the protocols should be highly adaptive to address the dynamic and non uniform nature of unreliable wireless channel link conditions; as such channels degrade quality of transmissions in a network [1]. In design of multi-hop routing protocols, end-to-end delay is a crucial design issue to consider in support for various quality of service (QoS) requirements for delay sensitive applications in WSNs.

Packet delays between a source node and a destination node can be a result of various factors in a WSN, such as heavy network traffic flow, high contention for transmission media access, number of intermediate nodes between a source node and a destination node, and time varying wireless channel link conditions to mention a few. Most of conventional routing algorithms aim to discover best routes by considering number of intermediate hops, in which case minimum-hop routes are given higher preference. However, routing protocols for WSNs should also take into account, the quality of channel links along a route for reliable communication, as the cost of using the route depends also on possible retransmissions for reliable communication. In densely deployed WSNs, multiple sensor nodes in close vicinity detect and respond to the same event almost all at the same time. The nodes detecting the event therefore compete for transmission medium access simultaneously, possibly leading to congestion which may have a significant impact on packet delays if not controlled properly by a medium access control (MAC) protocol.

The effects of dynamic transmission power control and best transmission distances on necessary number of intermediate nodes between a source node and a destination node have been extensively studied in literature. According to the work done in [2]-[6], network capacity can be improved by selection of the nearest neighbor by a routing protocol during transmission of packets from a source node to a destination through multiple hops. Depending on node distribution in a network, this is based on the intuition that decreasing the transmission distance between the source node and the destination node increases the number of hops required for packet transmissions, but allows for more concurrent transmissions which in turn increase network throughput. At the network layer, power control determines the neighborhood for a source node which affects selection of the next-hop node and influences the number of concurrent transmissions that can take place in the same vicinity at the MAC layer. Routes with a large number of short-distance hops may offer more energy-efficiency per node as transmission power requirements to relay packets to a nearby next-hop node along the link decrease with reduction in inter hop distance between the nodes [7]-[11]. However, as the number of intermediate nodes increases, transmitted packets may be subjected to increased packet error probability and more packet delays.

The rest of this paper is organized as follows: Section II presents the network model used in this work, together with problem formulation motivating the performed study. Section III describes the proposed modification to DSR protocol for minimizing delay, followed by performance analysis in Section IV. Finally, the concluding remarks in Section V.

II. SYSTEM MODEL AND PROBLEM DESCRIPTION

A. Network Model

In this work, a field gathering WSN application is assumed and investigated, whereby sensor nodes take spatial and temporal measurements for a given set of parameters in a sensor field. In this model, example network application could be monitoring the environment for catastrophic events, such as fire explosions in forestry industries. Each node collects data from the physical environment, as well as relaying the
data for other nodes to a base-station node. The base-station node is assumed to have relatively abundant resources as opposed to the sensor nodes which have severely limited resources in terms of memory, processing power, available bandwidth and energy from the small irreplaceable batteries. Only one base-station node exists in the used model.

We represent a WSN by a directed connectivity graph $G(N,E)$, where $N$ is a set of all the nodes in a WSN and $E$ is the set of all the pairs between nodes that can communicate directly. Each sensor node $n \in N$ has an isotropic transmission radius $R_s(n)$ and sensing radius $R_s(n)$. It is assumed that all the nodes have equal $R_s(n)$, which determines the set of nodes each node can directly communicate with; referred to as neighbor nodes. The set of nodes which are within $R_s(n)$ are represented by $N_{ab}(n)$ while all the other nodes are represented by $N_{ab}(n)$. Bidirectional and symmetric links exist between every source node and a neighbor node $m \in N_{ab}(n)$. Therefore for any two directly connected nodes $\{u,v\} \in N$, link$(u,v)$ is identical and symmetric to link$(v,u)$. Each node $n$ has a set of routes represented by $Routes(n)$ to a base-station, with each route $p_i(n) \in Routes(n)$ being the $i$-th route in node $n$ route-cache to the base-station. For simplicity, $R_s(n)$ and $R_s(n)$ are assumed to be equal for each sensor node throughout this paper.

B. Problem Formulation

In the described model, all the nodes which do not have the base-station node in their neighborhood rely on other intermediate nodes for transmission of packets. The work in this paper focuses on the problem of finding minimum-delay routes between each source node $n \in N$ and the base-station node $B_s$ in a WSN, with the objective to minimize end-to-end delay for transmission of packets. For each source node $n$ with $j$ multiple disjoint routes to the destination node $B_s$, a primary route $p_i(n) \in Routes(n)$ with minimum end-to-end delay satisfies the following expression:

$$p(n)_r = \min_{i=1, j}(p(n)_i).$$

(1)

The end-to-end delay along a route is also a function of wireless channel link errors as a result of required retransmissions for reliable communication. We therefore propose a routing cost function which satisfies (1), taking the link error rates along the established routes into consideration. The proposed routing cost function is implemented in dynamic source routing (DSR) protocol in [12] to improve its performance in a channel that is susceptible of link errors. The DSR protocol does not have a mechanism to adapt to the time varying conditions of a wireless channel for its routing decisions, but performs selection of a best route based on the number of intermediate nodes in each route to a destination node. However, a route with minimum number of hops is not necessarily the best route available to a destination node.

Several disjoint routes between a source node and a destination node are recorded, simply because non-disjoint routes would lead to quick depletion of energy from the common nodes along such routes [13]. Also, this ensures that link faults affect only one route per source node. Inasmuch as link error rates can be a major source of energy waste in WSNs as a result of packet retransmissions, error rates also affect the support for various QoS requirements for network applications, leading to poor network performance as a result. Hence why routing cost metrics should also incorporate wireless channel conditions for section of best routes.

C. Routing Cost Estimation

In this section, we derive a routing cost function for assessment of available routes between a source node and a destination node, which is a function of link error rates and end-to-end delay incurred by packets transmitted along the wireless channel links. The end-to-end delay $\delta_e(n,B_s)$ is the amount of time taken between packet creation at a source node $n$ and its reception at the destination node $B_s$. Along a route $p_i(n)$, each link $link(u,v) \in p_i(n)$ between any two neighbor nodes $\{u,v\} \in N$ introduces link delay $\delta_l(u,v)$ on a packet transmitted across the link. The end-to-end delay incurred along a $k$-th route is therefore given by

$$\delta_e(n,B_s)_k = \sum_{i=0}^{k-1} link(u,v)_l, \quad \forall\{u,v\} \in p_i(n)$$

(2)

where $h$ is length of the route in number of intermediate nodes. For each $i$-th link along the route, the delay incurred by a packet across the link is given by the following:

$$link(u,v)_l = \delta_{prop} + \delta_{tx} + \delta_{que}.$$  

(3)

where $\delta_{prop}$, $\delta_{tx}$ and $\delta_{que}$ are propagation delay, transmission delay and queuing delay respectively. The transmission delay is given by the ratio of packet size to channel data rate, which is the same for all the packets since the packet size and data rates have fixed values in this paper. The propagation delay is a function of the distance between two neighbor nodes over a link, with relatively small values compared to other types of delay associated with the link. The queuing delay is the amount of time spent by a packet in a buffer just before its transmission begins; which includes also, contention delay suffered by the packet while a node is competing for transmission media access. Moreover, queuing delay depends on the queue size, which is the number of packets awaiting transmission in a node buffer.

In a case of unreliable transmission channel in a WSN, increasing the number of intermediate nodes through which a packet is relayed increases the likelihood of transmission errors along the route. Assuming each link $link(u,v) \in p_i(n)$ between node $u$ and node $v$ along a route has an independent packet error probability $P_i(link(u,v))$, the end-to-end packet error rate along the entire route $P_r(p_i(n))$ is given by

$$P_r(p_i(n)) = 1 - \prod_{i=0}^{h-1}(1 - P_i(link(u,v))).$$

(4)

The work in [14] illustrates that using hop-by-hop packet error correction schemes can improve network throughput than using end-to-end error correction schemes. However, the hop-by-hop correction schemes induce more delays per-hop
and require more computational power from the intermediate nodes than necessary. Therefore error correction schemes in this paper are based on the end-to-end characteristics of a WSN, whereby the intermediate nodes simply receive and relay both data packets and error-correction packets between a source node and a destination node. In order to fully recover an erroneous packet, the number of packet retransmissions is therefore a function of end-to-end packet error rates along the route. The number of transmissions (together with possible retransmissions) required for successful delivery of packets from source node \( n \) to destination node \( Bs \) is a random variable \( X \) with a geometric distribution such that

\[
P_X(X = k) = \prod_{j=1}^{k-1} P_r^{-1}(p_i(n)) \times \left(1 - P_r(p_i(n))\right), \forall k.
\]  

(5)

It follows therefore that the mean number \( E[X] \) of individual packet transmissions for successful delivery of each packet is

\[
E[X] = \frac{1}{1 - P_r(p_i(n))}.
\]  

(6)

From (6) above, it can be deduced that the number of required transmissions for a reliable communication (transmission of a packet without errors) is reciprocal of the probability of successful delivery of a packet for each transmission. Then end-to-end delay \( \delta_e(n,Bs) \) is a function of individual link delays \( \delta_l(u,v) \) induced on each packet transmission through each link \( link(u,v) \) along route \( p_i(n) \) to a destination node. The expected end-to-end delay \( \delta_E(n,Bs) \) incurred for reliable transmission of each packet along the route between source node \( n \) and destination node \( Bs \) is then given by

\[
\delta_E(n,Bs) = \delta_e(n,Bs) \times \frac{1}{1 - P_r(p_i(n))}
\]  

\[
= \frac{\delta_e(n,Bs)}{\left(1 - P_r(link(u,v))\right)^k}.
\]  

(7)

Equation (7) illustrates the effect of the number of intermediate nodes required to relay packets between a source node and a destination node on end-to-end delay incurred by each packet for reliable transmission. Clearly, end-to-end reliability decreases with increasing number of intermediate nodes, which in turn increases end-to-end delay as a result of overhead due to necessary retransmissions to successfully deliver packets to a destination node. It can therefore be deduced that end-to-end delay increases exponentially with increasing number of intermediate nodes for a highly unreliable channel. Furthermore, (7) illustrates that at very low values of link packet error rates, the probability of transmission errors becomes relatively insignificant.

In case of hop-by-hop error correction schemes, transmission error at the specific link entails a need for retransmissions on that link in particular before relaying the packet further. Therefore the number of retransmissions on each link is independent of retransmissions on other links with a geometric distribution. As a result, the effect of such error correction schemes on the expected end-to-end delay reduces (7) to the following expression:

\[
\delta_E(n,Bs) = \sum_{i=0}^{h-1} \delta_l(n,Bs)_i \left(1 - P_r(link(u,v))\right).
\]  

(8)

The number of intermediate nodes \( h \) required to relay packets between a source node and a destination node is a function of node distribution and density \( p \) in a network and transmission radius \( R_i(n) \) for each node. Lower values of required relay nodes in a sparsely distributed network result in burden on energy requirements from each node since large transmission distances have to be covered, in which \( R_i(n) \) is also increased; while very large values of relay nodes may result in increased delay, contention and routing overhead in a case of source routing protocols. It follows then that an optimal value for the number of relay nodes is necessary for a given network node distribution. Fig. 1 depicts the number of required intermediate nodes to relay packets to a destination node on behalf of a source node. The distance \( d \) between any two nodes should be less than \( R_i \) for any two nodes to communicate directly, i.e. the nodes must be within each other’s transmission range, which makes them neighbors.

\[ D. \ \text{Packet Error Rate Estimation} \]

Packet error rate is the ratio of the number of incorrectly received packets to the number of packets transmitted. Each packet is incorrect if at least one of its bits is also incorrect when received. Therefore the rate of packet errors depends on the size of the packet in number of bits and the probability that each bit is received incorrectly. In this paper, signal-to-noise (SNR) based technique is used for estimating packet error rates on a link between any two nodes. SNR is simply a measure of the received signal strength \( P_{rx} \) in relation to background noise \( \eta \), given by the following expression [15]:

\[
SNR = \frac{P_{rx}}{I_{inter} + I_{extra} + \eta} \times PG
\]  

(9)

where \( I_{inter} \) and \( I_{extra} \) are intra-cell and extra-cell interference respectively, and \( PG = W/R_b \) where \( W \) is the spreading bandwidth and \( R_b \) is the bit-rate. From a received packet, the estimated \( SNR \) provides a basis for calculating bit error rates (BER) for the packet. BER is the ratio of the number of bits which are received incorrectly to the total number of bits transmitted over some time interval. BER therefore provides estimate for bit error probability along a

![Figure 1](source.png)

Source

Intermediate Nodes

\( S \rightarrow n_0 \rightarrow d \rightarrow n_1 \rightarrow \ldots \rightarrow n_{h-1} \rightarrow \text{Destination} \)

\( D \)

This figure illustrates the number of intermediate nodes \( h \) required to relay packets from a source node \( S \) to a destination node \( D \) each node with transmission radius \( R_i \) where \( n_i \) is the \( i \)-th intermediate node and \( d < R_i \).
link in a wireless channel. A packet of length $L$-bits on a link between node $u$ and node $v$ has packet error rate estimated by

$$P_e(\text{link}(u,v)) = 1 - \prod_{i=1}^{L} (1 - BER_i).$$

Although SNR based technique is used in this paper, it provides relatively accurate bit error rate estimations in free space environments. Any other suitable error estimation technique could still be employed. It is important to accurately estimate error rates as performance of routing protocols that include path reliability as a routing cost metric is also affected by the accuracy of error estimation techniques.

### III. Routing Protocol Description

This section presents the modification to DSR protocol proposed in this paper for delay sensitive WSN applications. The DSR in [12] is an on-demand source routing protocol which was originally designed for ad-hoc wireless networks to be completely self-organizing and self-configuring. A complete path for delivery of packets is included within the packet itself. Therefore the intermediate nodes only relay the packets without the overhead of performing further routing activities, such as establishing the next-hop node to which the packets should be relayed. The DSR protocol operates on two main mechanisms which are performed absolutely on-demand, route discovery and route maintenance. Routes are discovered by exchange of route request (RREQ) packets and route reply (RREP) packets among the network nodes.

#### A. Route Discovery

Route discovery is a mechanism through which a source node obtains a route to a destination node. This is performed only when the source node has data packets to send, but a route to the destination node does not exist yet in its route cache. The source node broadcasts a RREQ packet to all the nodes in the network. A node receiving the RREQ packet sends a RREP packet back to the source node if it is the destination of the RREQ packet or a route to destination exists in its route cache. Unlike the RREQ packet which is sent as broadcast, a RREP packet is sent as a unicast back to the source node. The costless option to deliver the RREP packet back to the source node is to send it along the same route traversed by the RREQ packet in reserve order of the intermediate nodes. Otherwise, the node receiving the RREQ packet rebroadcasts it further to its neighboring nodes. On receiving the RREP packet, the source node begins to transmit the packets for which the route discovery was initiated.

#### B. Route Maintenance

Route maintenance is a mechanism through which a source node detects route faults along an established route to a destination node. This is performed only when a source is using the route for transmission of packets. The source node keeps the route in its route cache for some timeout period after use, and finally deletes it from the route cache when the time out period expires. If any link breaks during packet transmission along the route, the node from which the link break is discovered sends a route error (RERR) packet to the source node about the broken link. On receiving the RERR packet, the source node invalidates the route in error from its route cache and uses an alternative route if it exists or reinitiates route discovery mechanism for another route to the destination node. The route maintenance mechanism verifies validity of the routes in use by the DSR protocol.

#### C. Proposed Modification

This section describes the modification proposed for the DSR protocol to minimize delay during transmission of packets in an unreliable wireless channel. The proposed modification necessitates the exchange of information about delay and packet error rates among the nodes for all the links comprising a route between a source node and a destination node. This is achieved by addition of two more fields in both the RREQ and RREP packets, and addition of one more field in the route cache for the cost associated with each route.

- $\delta_e$ Field: Records the end-to-end delay incurred by a packet along a route from a source node to a destination node, which can be calculated as shown in (3).
- $P_e(p(n))$ Field: Records the estimated packet error probability along the entire route, which is a function of number of relay nodes as calculated in (4).
- $\delta_e(n, Bs)$ Cost: Records the cost of individual routes in the route cache for each node. The cost is calculated as shown in (7), using both $\delta_e$ Field and $P_e(p(n))$ Field obtained from a received RREP packet.

When initiating a route discovery, a source node initializes the RREQ packet fields $\delta_e$ Field and $P_e(p(n))$ Field to 0 and 1 respectively. Any intermediate node processing the RREQ packet updates the field accordingly. A node initiating a reply inserts the values for $\delta_e$ Field and $P_e(p(n))$ Field into the RREP packet as obtained from the RREQ packet. On receiving the RREP packet, the source node calculates the cost for each route and inserts the route with its associated cost into the route cache table. A route with the lowest cost is selected as the current primary route and used for transmission of packets. To keep the protocol operations simple, RREQ packets must reach the destination node to reflect better, the current conditions of the wireless channel.

Wireless channel link conditions may vary instantaneously with time. The requirement that a RREQ packet must reach the destination node ensures that the obtained metrics used to estimate the routing cost give a correct status of the network about wireless channel links. The intermediate nodes replying to the request may otherwise provide stale values for the channel conditions. Also, a source node can record multiple disjoint routes to the same destination. This provides redundancy in case of route failures, in which case an alternative route will be readily available for immediate use.

### IV. Simulation and Results

#### A. Simulation Setup

This section presents performance analysis of the proposed modification to DSR protocol through simulations. We developed a discrete event driven simulator for WSNs implemented in C++ language. Table I shows simulation parameters based on CC2420 transceiver used in this paper.
Packet arrival rate was implemented with Poisson distribution for each node in a WSN. The maximum length of a route is limited to 14, as routes with large number of intermediate nodes would result in high routing protocol overhead since the entire route is included as part of the transmitted packets in source based routing. Fig. 2 shows the neighborhood of individual nodes in the performed simulation study, with the average of 6 neighbors per node.

B. Simulation Results

There are various metrics that can be used for performance evaluation of routing protocols. In this paper, the evaluation used is based on but not limited to network throughput and end-to-end delay. Throughput is simply the number of packets received successfully by the base-station node in a given time. Fig. 3 shows results for throughput in increasing channel link error rates. As the link gets worse with high error rates, network throughput drops due to unsuccessful packet transmissions. The modification proposed in this paper improves performance of the DSR protocol for throughput as illustrated by the simulation results in Fig. 3, whereby the modified DSR protocol outperforms the original version of the protocol. Fig. 4 presents simulation results for end-to-end packet delay in an increasingly unreliable channel. The modified DSR protocol also outperforms its predecessor by reducing the end-to-end delay incurred by packets between a source node and a destination node. This results from the proposed routing cost function which takes into account packet delay as one of the metrics that can be used to determine the cost of each route to a destination node.

In Fig. 5, a comparison is presented for the effects of using end-to-end error correction schemes against hop-by-hop on routing protocols. The results illustrate that routing protocols which include link reliability for routing metrics perform better in end-to-end schemes in low error rates and small number of intermediate nodes. As both the error-rates and number of intermediate nodes increase, hop-by-hop schemes become a better option. End-to-end delay increases linearly with the increase in number of intermediate nodes required to relay packets along unreliable routes when using hop-by-hop error correction schemes, and exponentially with end-to-end.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor network field</td>
<td>650 x 650 Meters</td>
</tr>
<tr>
<td>Number of nodes (N)</td>
<td>100 Nodes</td>
</tr>
<tr>
<td>Transmission range (R_i(n))</td>
<td>85 Meters</td>
</tr>
<tr>
<td>Transmit energy (E_t)</td>
<td>142.20 x 10^3 Joules/Second</td>
</tr>
<tr>
<td>Receive energy (E_r)</td>
<td>88.20 x 10^3 Joules/Second</td>
</tr>
<tr>
<td>Sleep energy (E_sleep)</td>
<td>90.00 x 10^6 Joules/Second</td>
</tr>
<tr>
<td>Transmission rate</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Packet size</td>
<td>32 Bytes</td>
</tr>
<tr>
<td>Initial energy per node</td>
<td>2 Joules</td>
</tr>
</tbody>
</table>

Table I: Simulation Parameters

Figure 2. Individual nodes neighborhood. This gives the number of neighbors for each node in a WSN. The neighbor nodes are those which are within one-hop transmission distance from a source node. The average number of neighbors per node in this distribution is 6.

Figure 3. Network throughput measured against increasing packet error rates for wireless channel links. The overall throughput decreases with increasing error rates due increasing number of unsuccessful packet transmissions across the unreliable links.

Figure 4. The effect of increasing packet error rates on end-to-end delay. Both end-to-end delay and packet error rates provide a good measure of transmission channel links on which a routing protocol can assess routes. High error rates lead to increase in number of packet retransmissions for reliable communication in a network.
The number of intermediate nodes \( h \) can significantly affect overall performance of a WSN if not chosen carefully, as it was shown in (7) and (8). Fig. 6 illustrates the effect of \( h \) on end-to-end delay for various link error rates. It can be deduced from the figure that proper values of \( h \) should be chosen in consideration to reliability of wireless channel links by a routing protocol to adapt well for reliable communication.

V. CONCLUSION

In this paper, modification to DSR protocol has been proposed, with the aim to improve performance of the DSR protocol taking into account, unreliability of wireless channel links in delay intolerant WSN applications. A routing cost metric was derived and implemented in the modified DSR protocol to reduce end-to-end delay incurred by packets between a source node and a destination node. Based on simulation results which demonstrate improved performance by the modified DSR protocol, it becomes empirical to deduce that routing protocols should consider the quality of channel links along a route for reliable communication; as the cost of using the route depends also on the possible retransmissions incurred along such route. Also, hop-count alone does not provide a good measure for a routing cost.

REFERENCES


