Energy-Efficient Dynamic Source Routing Protocol for Wireless Sensor Networks

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Summery
Routing presents a significant design challenge to meet various applications requirements in wireless sensor networks (WSNs) communications. In this paper, we present a minimum delay multipath routing protocol with modification to the standard dynamic source routing (DSR) protocol, which aims to improve energy efficiency and minimize end-to-end delay to provide quality of service (QoS) support for delay sensitive applications in WSNs. The presented Energy-Efficient DSR (EEDSR) protocol takes into account, end-to-end delay and reliability of wireless channel links to establish a routing metric used to determine the cost associated with individual routes between a source node and a destination node. Each source node records multiple disjoint routes to the same destination. Selection of the primary route for data transmissions is based on the derived routing metric to give preference to the most reliable route with minimum end-to-end delay, reducing energy consumption which would otherwise be incurred during packet retransmissions for reliable communication. Simulation results reveal improved performance by the EEDSR protocol in comparison with the standard DSR protocol, most importantly when used for routing in unreliable channel link conditions with high error rates.

Key words:
Channel Reliability, Energy-Efficiency, Error-Rates, Routing Protocols, Wireless Sensor Networks (WSNs).

1. Introduction

Wireless sensor networks (WSNs) are special types of networks driven by advances in micro electro mechanical system (MEMS) and proliferation of various suitable network applications in both civilian and military domains [1]. 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 communication protocols for WSNs should be designed to be self-organizing and self-configuring. Hence, the protocols should be highly adaptive to address the dynamic and non uniform nature of unreliable wireless channel link conditions associated with WSNs; as such channels degrade the quality of transmissions in a network [2]. 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 to relay packets between a source node and a destination node and the time varying wireless channel link conditions to mention a few. Most of conventional routing algorithms aim to discover best routes by considering number of relay nodes (hop-count), 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 [3].

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 overall network performance if not coordinated 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 research works reported in [4]-[8], 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 node 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 increases network throughput [6]. At the network layer, power control determines the neighborhood information 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

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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 [9]-[14]. However, as the number of intermediate nodes to relay packets increases, the transmitted packets may be subjected to increased packet error probability and end-to-end packet delays [3].

Power associated with packet transmissions may often be assumed to dominate energy consumption in WSN designs [8], [10], [12]. Energy tradeoffs across hardware and software platforms are normally part of design techniques aiming to reduce the energy consumption. There are various sources of energy waste in WSN communications which include idle listening, control packets overhead, erroneous packet retransmissions and overhearing packets destined for other nodes. Moreover, energy consumption associated with the exchange of routing control packets alone is significant and non negligible, in as much as packet transmission is one of the most energy-expensive operations. Consequently, research in design of routing protocols for WSNs mostly focuses on development of energy-efficient algorithms which minimize energy consumption for individual nodes in a network, prolonging the overall network-lifetime as a result [13].

The rest of this paper is organized as follows: Section 2 presents the system model used in this work, followed by problem formulation motivating the conducted study in Section 3. Section 4 describes the proposed modification for the energy-efficient dynamic source routing (EEDSR) protocol for minimizing energy consumption and packet delays; while Section 5 presents the simulation based performance evaluation of the EEDSR protocol in comparison with the standard dynamic source routing (DSR) protocol. Finally, the concluding remarks in Section 6.

2. System Model

2.1 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, an example network application could be monitoring the environment for catastrophic events, such as fire explosions in agriculture and forestry industries. Each node collects data from the physical environment, as well as relaying data packets on behalf of other nodes which are not directly connected to a sink node. Unlike all other nodes, the sink 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, usually hard to replace and non rechargeable batteries. Assuming further, the existence a single sink node to which all the network data packets in this model are transmitted.

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

2.2 Channel Model

The wireless channel model emulates the time-varying and non uniform characteristics of a transmission channel, whereby transmitted signal strength is subject to distance loss, shadowing and multi-path fading as it propagates through the air interface. Exponential path loss model with log-normal fading effects for the wireless channel between any two nodes is considered in this work. This channel model has been experimentally shown to accurately model the low power communication in WSNs as illustrated by the work previously conducted and reported in [14]; which has also been widely adopted and most commonly used for analytical studies and simulations in WNS communications.

In this model, the path-loss is the change in received signal strength over a distance between a transmitter node and receiver node. Following [14]-[16], the path-loss $PL(d)$ at distance d in meters is given by the following expression:

$$PL(d)dB = \overline{PL}(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (1)$$

where $\overline{PL}(d_0)$ is the path-loss in dB at distance d_0 (whereby d_0= 1meter), n is the path-loss attenuation factor and X_σ is a zero mean Gaussian random variable with a standard deviation of σ (in dB). The $X_\sigma$variable represents the shadowing effect on the transmitted signal through a wireless channel. In this work, a plain ground is considered for the values of n and σ to be 3.12 and 1.83 respectively, as indicated by the work in [16] for a one slope path-loss propagation model, with reference to Table 1 below. The received signal strength $P_{Rx}(d)$ is therefore given by

$$P_{Rx}(d) = P_{Tx} - PL(d) \quad (2)$$

where d is the distance between a transmitting node and a receiving node. The expression in (2) above provides the received signal strength as a function of distance separating any two communicating sensor nodes.

2.3 Traffic Model

Traffic models in WSNs depend largely on network applications and behavior of sensed events [17]-[19]. In this work, each node generates data messages for the sink node. We assume that the message arrivals follow an independent and identically distributed (*i.i.d.*) Poisson process with varying number of packets per message but identical packet length fixed at 64 bytes. In addition to the messages generated locally by each node, any node can cooperatively relay packets originated by other nodes. Further, we assume that the distribution for the number of message arrivals X generated by each node n during the time interval between t_i and $(t_i + T)$ with the average message arrival rate of λ_n per node is given by the following expression [17]:

$$P(X = k) = \frac{(\lambda_n T)^k}{k!} e^{-\lambda_n T}, \qquad k > 0, \quad (3)$$

where k is a non-negative integer. We assume also that the

Table 1: Channel Model Parameters

Parameter	Value
Propagation model	log-normal
Path-loss exponent	3.12
Standard deviation (σ)	1.83

inter-arrival times for the generated messages follow an exponential distribution with a probability density function (pdf) $f_X(x) = \lambda_n e^{-\lambda_n x}$ for $x \geq 0$. The nodes which are located in close vicinity to the sink node will have a high duty cycle compared to other nodes further away. Proper assumptions of realistic traffic models in performance evaluation of protocols in WSNs are important for accurate modeling and analysis, which ensures that protocols for WSNs are designed as effectively as possible [17].

3. Problem Description

3.1 Problem Formulation

In the described network model above, all the nodes which do not have the sink node in their neighborhood rely on other intermediate nodes for transmission of packets through multihop communication. In the case of WSNs, determining the routes which minimize energy consumption is a crucial design consideration since energy resources are extremely scarce for the sensor nodes. The work in this paper focuses on the problem of finding minimum-delay and reliable routes between each source node $n \in N$ and the sink node D in a WSN, with the objective to minimize energy consumption and end-to-end delay for reliable transmission of packets to the sink node. For each source node n with j multiple disjoint routes to the sink node, a primary route $p(n)_r \in Routes(n)$ with minimum energy consumption and end-to-end packet delay satisfies the following expression:

$$p(n)_r = \underset{i=1..j}{\text{Min}}\big(p_i(n)\big). \quad (4)$$

The end-to-end delay along a route is also a function of wireless channel link errors as a result of retransmissions for reliable communication. We therefore propose a routing cost function which satisfies (4), taking the link error rates along the established routes into consideration. The proposed routing cost function is implemented in the EEDSR protocol with modification to the standard dynamic source routing (DSR) algorithm [20] to improve performance in a channel that is susceptible of link errors. Like other conventional routing algorithms, the standard 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 to a destination node. However, a route with minimum number of hops is not necessarily the best route available to the destination node in WSN communications, as priority is usually given to long distance-hops which are subject to low signal-to-noise ratio [7]-[8], [12], [19].

Several disjoint routes between a source node and a destination node are recorded, simply because non-disjoint routes would otherwise lead to quick depletion of energy from the common nodes along such routes [8], [21]; which also ensures that link faults affect only one route per source node. In as much as link error rates can be a major source of energy waste in WSNs as a result of packet retransmissions, the error rates also affect the support for various QoS requirements for network applications, leading to poor network performance as a result. Hence why the routing cost metrics should also incorporate wireless channel conditions for section of the best routes for delivery of packets [3], [9].

3.2 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 through the wireless channel. The end-to-end delay $\delta_e(n, D)$ is the amount of time taken between packet creation at a source node n and its reception at the sink node D. Along a route $p(n)$, each link $link(u, v) \in p(n)$ between any two neighbor nodes $\{u, v\} \in N$ introduces link delay $\delta_l(u, v)$ on a packet transmitted through the wireless channel. The end-to-end packet delay incurred along a k-th route is therefore given by

$$\delta_e(n, D)_k = \sum_{i=1}^{h+1} \delta_l(u, v)_i, \qquad \{u, v\} \in p_i(n) \tag{5}$$

where h is length of the route in number of intermediate nodes required to relay the transmitted packets to the sink node. For each i-th link along the route, the delay incurred by a packet across the link is given by the following:

$$\delta_l(u, v)_i = \delta_{Prop} + \delta_{Tx} + \delta_{Que}, \tag{6}$$

where δ_{Prop}, δ_{Tx} and δ_{Que} are propagation delay, transmission delay and queuing delay respectively. The transmission delay is given by the ratio of packet size to the 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 coordinated by MAC layer protocols. Moreover, queuing delay depends also on the queue size of each node, which is the number of packets awaiting transmission in the node buffer.

In the case of unreliable wireless transmission channel in WSN communications, increasing the number of intermediate nodes through which a packet is relayed also increases the likelihood of incurring packet transmission errors along the route [1], [3], [8]-[7], [9], [12]. Assuming that each link $link(u, v) \in p_i(n)$ between node u and node v along a route has an independent packet error probability $P_r(\mathrm{link}(u, v))$, the end-to-end packet error rate along the entire route $P_r(p_i(n))$ is given by the following expression:

$$P_r(p_i(n)) = 1 - \prod_{i=1}^{h+1} (1 - P_r(\mathrm{link}(u, v))_i). \tag{7}$$

The work in [22] 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 can induce more packet delays per-hop and require more computational power from the intermediate nodes than necessary, which is not ideal in WSNs since computational resources are also scarce. 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 D is a random variable X with a geometric distribution such that [23]

$$P_r\{X = k\} = \prod_{j=1}^{k-1} P_r\big(p_i(n)\big)_j \times \Big(1 - P_r\big(p_i(n)\big)\Big), \forall\, k. \tag{8}$$

It follows therefore that the mean number $E[X]$ of individual packet transmissions for successful delivery of each packet is given by the following expression:

$$E[X] = \frac{1}{1 - P_r\big(p_i(n)\big)}. \tag{9}$$

From (9) above, it can be deduced that the number of required transmissions for 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 $\delta_e(n, D)$ 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 $\delta_E(n, D)$ incurred for reliable transmission of each packet along the route between source node n and destination node D is then given by

$$\delta_E(n, D) = \delta_e(n, D) \times \frac{1}{1 - P_r\big(p_i(n)\big)} \tag{10}$$

$$= \frac{\delta_e(n,D)}{\left(1 - P_r\left(\text{link}(u,v)\right)\right)^{(h+1)}}.$$

Equation (10) above 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 the overhead due to necessary retransmissions to successfully deliver packets to a destination node. It can therefore be deduced again that end-to-end delay increases exponentially with increasing number of intermediate nodes for a highly unreliable channel. Furthermore, (10) illustrates that at very low values of link packet error rates, the probability of transmission errors becomes relatively insignificant.

In the case of hop-by-hop error correction schemes, a 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 (10) to the following expression:

$$\delta_E(n,D) = \sum_{i=1}^{h+1} \frac{\delta_l(n,D)_i}{\left(1 - P_r\left(\text{link}(u,v)\right)_i\right)}. \qquad (11)$$

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 ρ in a network and transmission radius $R_t(n)$ for each node [12], [19], [21]. 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 $R_t(n)$ 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 [27]. 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_t for any two nodes to communicate directly, *i.e.* the nodes must be within each other's transmission range, which makes them neighbors.

3.3 Packet Error Rate Estimation

In this work, a signal-to-interference and noise ratio ($SNIR$) based technique is used for estimating packet error rates on a link between any two nodes. Each packet is considered incorrect if at least one of its bits is also incorrect when received, without employing error correction schemes. Therefore the packet error rate depends on the size of the packet in number of bits and the probability that each bit comprising the packet is received incorrectly.

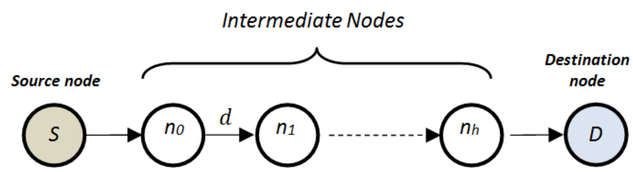

Fig. 1: Multihop communication through intermediate nodes.

The $SNIR$ for a packet received by each node in a direct sequence code division multiple access (DS-CDMA) based communication system with independent and direct-sequence simultaneous transmitting nodes S_{Tx} is simply a measure of the received signal strength P_{Rx} in relation to the background noise η and inter-node interference [24], given by [25]-[26]:

$$SNIR = \frac{P_{Rx}}{\eta + I_{S_{Tx}}} \times PG, \qquad (12)$$

where P_{Rx} is the useful received power level, $I_{S_{Tx}}$ is the inter-node interference and η is he background noise intensity; PG is the direct sequence spread-spectrum (DSSS) processing gain given by the ratio W/R_b; where W is the spreading bandwidth and R_b is the bit-rate, which is dependent on coding and modulation scheme used. The total inter-node interference power is the sum of interference powers (P_{Rx_int}) from each all the nodes transmitting simultaneously within a neighborhood, given by

$$I_{S_{Tx}} = \sum_{i=1}^{S_{Tx}} \left(P_{Rx\_int}\right)_i. \qquad (13)$$

For each node, S_{Tx} is a random variable since the number of interfering nodes varies from time to time. From a received packet, the estimated $SNIR$ provides a basis for calculating bit-error rate (BER) for the packet, which is also dependent on the modulation scheme used as mentioned earlier in this section. Following the work in [27], similar assumptions are also made in this paper about the additive white Gaussian noise (AWGN) and binary phase shift keying (BPSK) modulation and coding scheme to estimate the average BER experienced by each node, given by the following:

$$BER = \frac{1}{2} \times erfc\left(\sqrt{\frac{P_{Rx}}{(\eta + I_{S_{Tx}})} \times \frac{W}{R_b}}\right) = \frac{1}{2} \times erfc\left(\sqrt{SNIR}\right) \quad (14)$$

where the $erfc$ is the complementary error function [28]. However, the main focus of the work in this paper is not on the details of any specific modulation scheme, but to study the dependence of packet error rates on the received power levels. In a measurement study previously conducted for WSN communications, the authors in [29] reported that their empirical results closely matched with (14) above for validation. The calculated BER provides the estimate for packet error probability through a link in a wireless channel. A packet of length L-bits through a link between node u and node v has packet error rate estimated by

$$P_r\big(link(u, v)\big) = 1 - \prod_{i=1}^{L}(1 - BER_i). \quad (15)$$

Although the $SNIR$ based technique is used in this paper, it has been established that it provides relatively accurate bit error rate estimations in free space environments [30]. Any other suitable error estimation techniques could still be employed. In essence, numerous previous works in literature reported that it is important to accurately estimate link error rates as performance of routing protocols that include route reliability as a routing cost metric is directly affected by the accuracy of wireless channel link error estimation techniques employed [9], [14], [30]-[32], in which case the inaccurate modeling may lead to incorrect evaluation in protocol design.

4. Routing Protocol Description

This section presents the proposed modification to the standard DSR protocol in [15], which forms the basis for the discussed EEDSR protocol, specifically for delay sensitive WSN applications. The standard DSR protocol is reactive and source based routing protocol which was originally designed for ad-hoc wireless networks to be completely self-organizing and self-configuring without any administration [15], [20]. A complete route for delivery of packets is included within the packet itself by a source node. 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 standard DSR protocol operates on two main routing mechanisms which are performed absolutely on-demand, *route discovery* and *route maintenance*. Routes are established through the exchange of route request (RREQ) packets and route reply (RREP) packets through the network.

4.1 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 data packets for which the route discovery was initiated.

4.2 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.

4.3 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 the addition of one more field in the route cache for the cost associated with each route.

- δ_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 (6).
- $P_r(p(n))\_Field$: Records the estimated packet error probability along the entire route, which is a function of number of relay nodes as calculated in (8).
- $\delta_E(n, D)\_Cost$: Records the cost of individual routes in the route cache for each node. The cost is calculated as shown in (10), using both δ_e_Field and $P_r(p(n))\_Field$ obtained from a received RREP packet.

When initiating a route discovery, a source node initializes the RREQ packet fields δ_e_Field and $P_r(p(n))\_Field$ 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 δ_e_Field and $P_r(p(n))\_Field$ 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.

In addition to the modifications described above, the EEDSR protocol operations adhere to same on-demand routing mechanisms as the standard DSR protocol. Fig. 2 illustrates the required information exchange for the routing metrics on which the routing cost function is based. Wireless channel link error rates are estimated from the $SNIR$ of the received signal from the physical layer and the reliability of a candidate route is then determined from the link error rates of individual links comprising the route. The wireless channel link conditions may vary instantaneously from time to time. The requirement that a RREQ packet must reach the destination node in the EEDSR protocol ensures that the obtained metrics used to estimate the routing cost give 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. As mentioned in previous sections, 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.

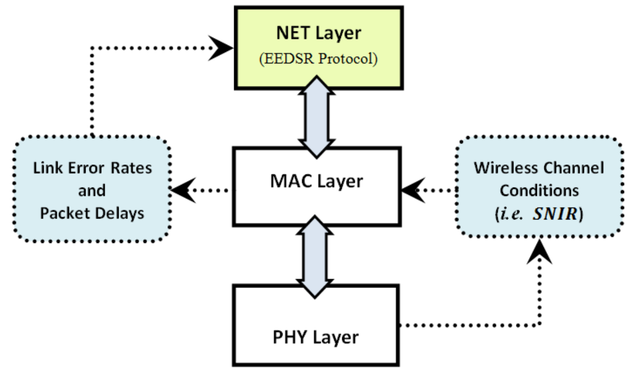

Fig. 2: The EEDSR protocol information exchange.

5. Simulation and Results

5.1 Simulation Setup

This section presents performance analysis of the proposed modification to the DSR protocol through simulations. We developed a discrete event driven simulation program for WSNs implemented in C++ language. Table 2 shows simulation parameters based a low cost and highly integrated Chipcon CC2420 radio transceiver module that was designed for low power and low voltage wireless applications [33]. The CC2420 transceiver has been widely used in literature and practical experimentations in WSNs [8], [19], [21], [34]-[35].

To investigate the effects of wireless channel link error in simulations, the perfect knowledge of link error rates is first assumed with reference to the work presented in [36], [37]. Considering real a situation in WSNs communications, assuming a perfect link error estimation scheme that provides accurate values is valid when using the CC2420 transceiver as it provides link quality values and received signal strength measurements [33]. Based on the knowledge of link errors, performance of the EEDSR and DSR protocols is examined using a random packet error model. For each wireless channel link in this model, a uniformly distributed random link error rate is assigned such that the following holds [37]:

$$0 < P_r(link(u,v) \leq P_r(link(u,v)_{MAX}, \qquad (16)$$

where $P_r(link(u,v)_{MAX}$ is the maximum value of link error rate. The maximum link error rate is then varied for different degrees of the wireless channel link quality. Alternatively, the error estimation technique described in the previous section is used based on the model in (14) to model channel link reliability. Moreover, the maximum length of each route is limited to 14 intermediate nodes, 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 [15].

Table 1: Simulation Parameters

Parameters	Values
Sensor network field	$500m$ x $500m$
Number of nodes (N)	100 Nodes
Transmission range ($R_t(n)$)	25 Meters
Current consumption (Rx)	18.8 mA
Current consumption (Tx)	17.4mA
Current consumption	426.0 µA
Data rate	250 kbps
Packet size	64 Bytes
Routing control packet	32 Bytes

5.2 Performance Metrics

There are various metrics that can be used to evaluate performance of routing protocols, and a good attention is required for selection of the appropriate metrics. The following are metrics considered in this work for evaluation of the proposed routing protocols:

- *Average end-to-end delay*: This is the average end-to-end delay suffered by data packets from arrival time at the source node till received by the destination node, this includes route acquisition delay, transmission delay and propagation delay through a wireless channel.
- *Energy consumption*: A measure of the rate at which energy is consumed by sensor nodes in a WSN within a specific time period, which is the reciprocal of energy consumption by the nodes. Energy efficient communication occurs with minimal possible energy consumption for each sensor node during packet transmissions in a network.
- *Average network throughput*: The average number of data packets successfully received by the sink node per unit time, measured in kbps. This metric measures the effectiveness of routing protocols on packet delivery through multi-hop communication.
- *Packet delivery ratio*: Packet loss measures the rate at which packets are lost in a WSN, while delivery ratio is the ratio of the total number of packets successfully received by the sink node to the number of packets sent by all the sensor nodes in the network.

Based on the aforementioned performance metrics, the next section presents the simulation based performance evaluation results and discussion for the presented work in this paper.

5.1 Simulation Results and Discussion

The DSR protocol and EEDSR protocol are evaluated for varying message arrival rate and channel link error rates in this subsection. Fig. 3 shows the neighborhood information of individual nodes for the simulation configuration in the performed study, with the average of 6 and a maximum of 12 neighbors per node. Fig. 4 and Fig. 5 present the results for energy consumption for the DSR protocol and the EEDSR protocol with increasing message arrival rate and link error rate respectively. The figures illustrate reduced energy consumption by the EEDSR protocol for reliable delivery of packets to the sink node (for both transmissions and retransmissions). The reduced energy consumption by the EEDSR protocol is the result of the new routing metric which includes channel reliability for assessment of available routes.

Further, Fig. 6 and Fig. 7 presents results for network throughput, which illustrate improved through by the EEDSR protocol. The improvement in average network throughput results from using reliable routes for packets delivery to the sink node, reducing the overall packet loss probability along the selected routes. Fig. 8 and Fig 9 present results for the average end-to-end delay incurred by the transmitted packets. Routes used by the EEDSR protocol are more reliable with reduced packet loss; hence reduced packet retransmissions along the selected routes. As a result, the EEDSR protocol reduces the average end-to-end delay incurred by the transmitted packets during packet delivery.

Finally, Fig. 10 and Fig. 11 present results for packet delivery for increasing message arrival rate and link error rates; whereby the EEDSR protocol outperforms the standard DSR protocol with high packet delivery ratio. Hence, less packet loss and improved network throughput as illustrated in Fig. 6 and Fig. 7. In summary, the simulation results in this work results reveal improved performance by the EEDSR protocol when used for routing in unreliable WSNs with high link error rates. The presented results reveal also that the conventional routing algorithms such as the standard DSR protocol which use hopcount for assessment of available routes are inefficient for reliable delivery of packets in multihop WSN communications.

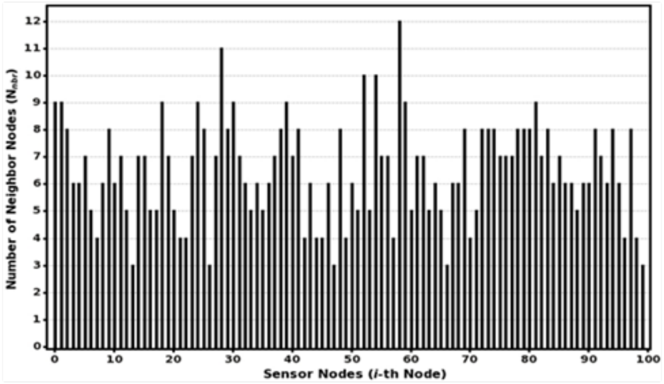

Fig. 3: Network neighborhood information.

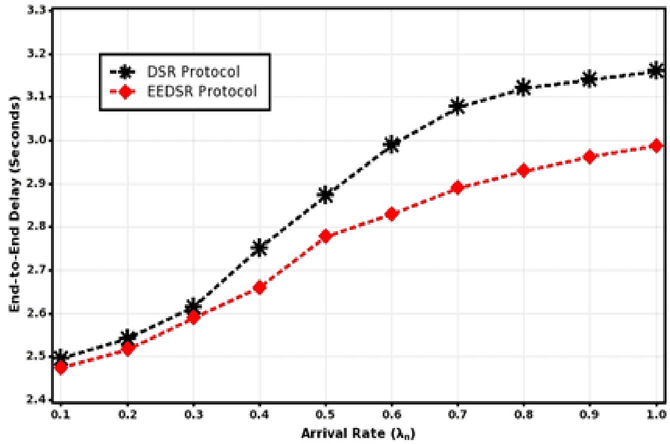

Figure 8: End-to-end delay versus arrival rate.

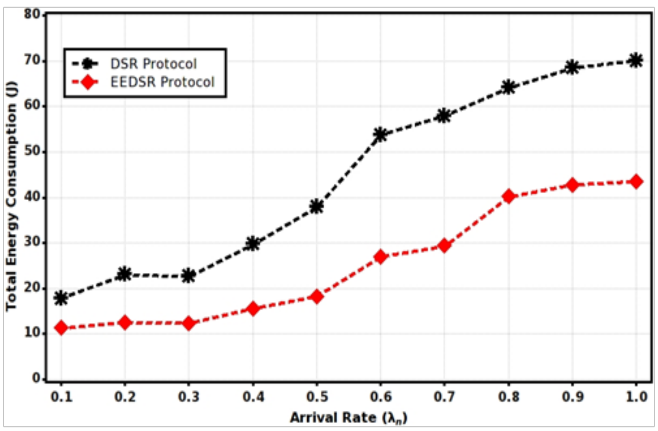

Fig. 4: Energy consumption versus arrival rate.

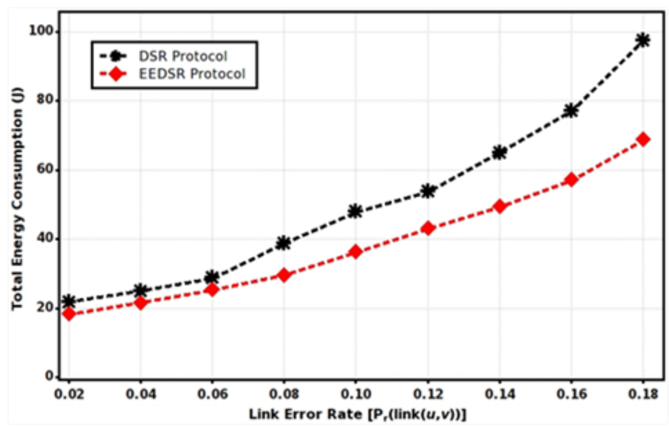

Fig. 5: Energy consumption versus link error rates.

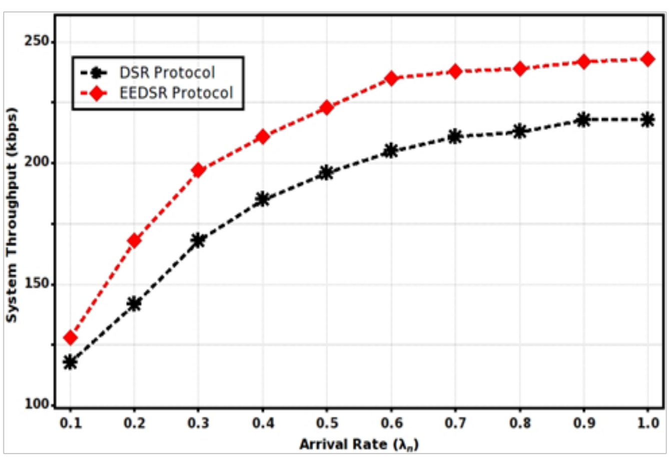

Fig. 6: Network through versus arrival rate.

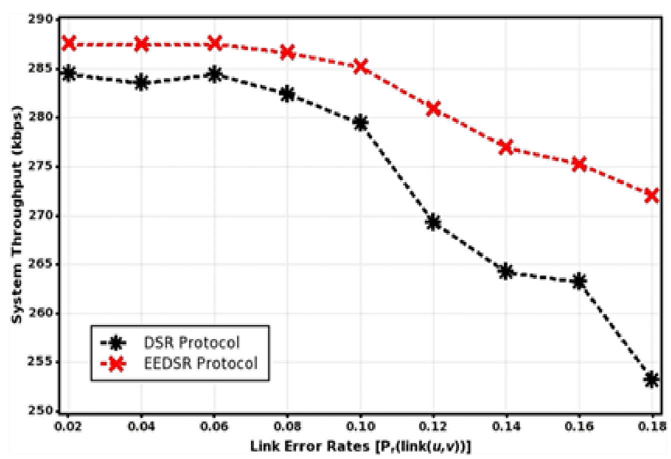

Fig. 7: Network throughput versus link error rates.

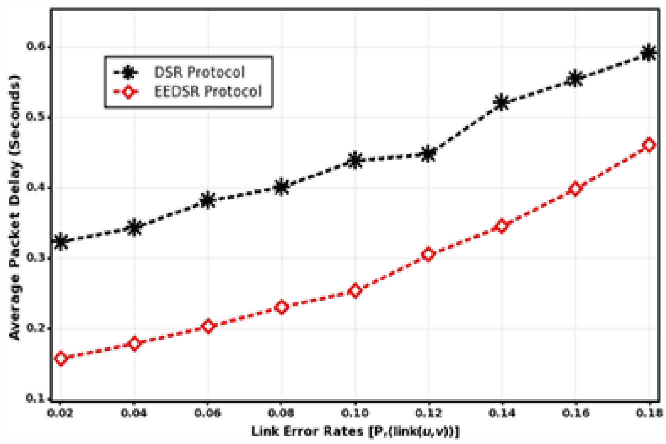

Fig. 9: End-to-end delay versus link error rates.

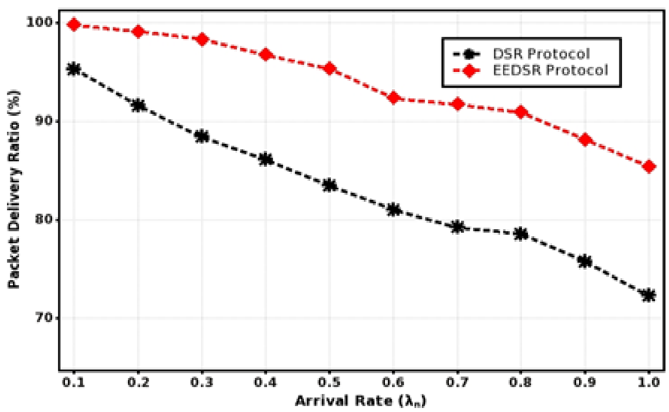

Fig. 10: Packet delivery ratio versus arrival rate.

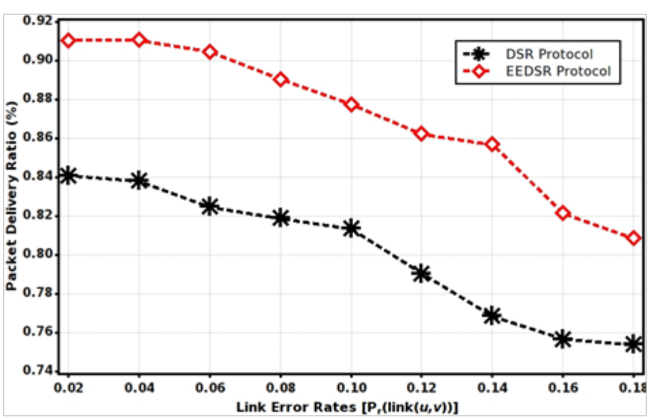

Fig. 11: Packet delivery ratio versus link error rates.

Concluding Remarks

In this paper, modification to the standard DSR protocol has been presented, with the aim to improve performance by taking into account, reliability of wireless channel links for delay intolerant WSN applications. A new routing cost metric was derived and implemented in the EEDSR protocol to reduce end-to-end delay incurred by packets between a source node and a destination node. Based on the simulation results which demonstrate improved performance by the EEDSR protocol, it can be concluded that routing protocols should consider the quality of channel links along a route for reliable communication; as the cost of using the routes depends also on the possible retransmissions incurred along such routes. Furthermore, the work in this paper illustrates that hopcount alone does not provide a good measure for a routing cost, but combined with other metrics for assessment of routes.

Acknowledgements

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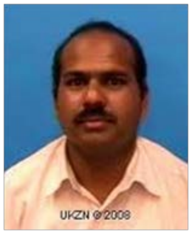

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