SUMMARY One of the major challenges facing the design of a routing protocol for Wireless Sensor Networks (WSNs) is to find the most reliable path between the source and sink node. Furthermore, a routing protocol for WSN should be well aware of sensor limitations. In this paper, we present an energy efficient, scalable, and distributed node disjoint multipath routing algorithm. The proposed algorithm, the Energy-aware Multipath Routing Algorithm (EMRA), adjusts traffic flows via a novel load balancing scheme. EMRA has a higher average node energy efficiency, lower control overhead, and a shorter average delay than those of well-known previous works. Moreover, since EMRA takes into consideration network reliability, it is useful for delivering data in unreliable environments. 

**key words:** multipath routing, load balancing, energy efficient routing, probability of successfully delivering, fault tolerance

1. Introduction

Wireless Sensor Networks (WSNs) have recently emerged as an important technology that can be applied in Smart Homes and interactive human environments [1]. Implementation of WSNs, however, involves several problems such as the limitations of sensor nodes, communication bandwidth, and, more importantly, battery power [2]. For these WSN environments, earlier works have explored the design of mechanisms for single path routing. In order to route around failed nodes, these previous protocols assumed a periodic, low-rate, flooding of events that enabled local rerouting; however, such flooding can adversely impact the energy efficiency of WSN. Hence, it is desirable to find alternative concepts for rerouting in order to provide greater resilience after failures [3].

Many routing algorithms have been proposed to overcome the aforementioned limitations of WSN. There are basically two categories of WSN routing protocols in the literature, cluster-based and flat. Cluster-based routing protocols divide the network into clusters and utilize a sleep mode to save energy and prolong the network lifetime. One node is selected as the cluster head for each cluster, and this cluster head receives and aggregates data packets from its members before forwarding the data to a sink node. Examples of cluster-based routing protocols include LEACH [4], TEEN [5], and APTEEN [6]; the latter tries to directly reduce routing overhead by using only localized information. There are three types of flat routing protocols, namely, flooding, forwarding, and data-centric-based routing protocols. There are several types of data-centric-based routing protocols whose use is determined by whether the sink broadcasts the attribute for data (reactive protocol), e.g., Directed Diffusion (DD [7]), or the sensor nodes broadcast an advertisement for the available data and wait for a request (proactive protocol), e.g., Sensor Protocols for Information via Negotiation (SPIN [8]).

Classical multipath routing has been used extensively in the literature to achieve load balancing [9], [10] and fault tolerance [11], [12] in computer networks; high speed networks serve as one example of this type of routing [13]. Load balancing splits traffic among the reliable multiple paths connecting the source to the sink node. Thus fault tolerance or robustness is an inherent feature of multipath routing. Robustness refers to the number of alternate paths that can be substituted between the source and sink node when the primary path has failed. As described in Fig. 1, fault tolerant routing mechanisms [14] for ad-hoc networks include route repair, first. After detecting a break in link $x - y$, node $x$ can repair the route by finding another node $z$ such that $x - y$ can be replaced by $x - z - y$. Alternate routing is a scheme whereby the source searches for a full alternate route after a failure, and redundant routing refers to the establishment of alternate paths before the failure.

In reference paper [15], multipath routing is formulated as a linear programming problem with the objective of maximizing the network lifetime. In [16], multipath routing is formulated as a constrained optimization problem by using deterministic network calculus. Previous work by [17], [18] proposed the well-known Energy-Efficient Multipath Routing Protocol (EEMRP); however, this protocol considers only hop-count and node residual energy to reduce the energy consumption and does not also take into account network reliability.

In this paper, we propose a distributed, scalable, and lo-
calized multipath algorithm to discover node disjoint paths between the source and the sink nodes. Furthermore, a load balancing algorithm is proposed to distribute the traffic over the multiple paths discovered. Lastly, the proposed algorithm takes network reliability into consideration. We compare our proposed scheme, the Energy-aware Multipath Routing Algorithm (EMRA), with DD and EEMRP. Simulation results show that EMRA has higher node energy efficiency, lower control overhead, and shorter average delay than that of the other protocols.

The remainder of this paper is organized as follows. Section 2 explains previous work on WSNs, Sect. 3 presents details of the proposed algorithm, Sect. 4 evaluates our proposal by employing a simulation model, and finally, Sect. 5 concludes the paper.

2. Previous Work

The objective of this paper is to develop an algorithm to identity efficient multiple paths from a source node to a sink node in WSN. Since WSN environment generally has a constrained energy problem, one of the limitations mentioned previously, a large number of routing protocols have recently been introduced. Directed Diffusion (DD [7]) is the representative scheme of reactive protocols and consists of four phases based on flooding: Interest, Gradient, Data transmission, and Reinforcement, as shown in Fig. 2. In DD, data generated by sensors is named using attribute value pairs. A sensing task is disseminated throughout the sensor network as an interest for named data. This dissemination sets up gradients within the network designed to draw events (i.e., data matching the interest). Events begin by flowing towards the originators of interests along multiple paths. Subsequently, the sensor network reinforces either one or a small number of these paths, and since DD uses only the selected paths from this time, the total network lifetime may be short. Furthermore, the major drawback of DD, with respect to energy efficiency, is periodic flooding of low-rate events. The low-rate flooding scheme notifies the sink and other nodes of available alternate paths, and the periodicity of flooding determines the temporal accuracy of alternate path characteristics.

Energy Aware Routing (EAR) [19] is one of the routing algorithms that improves upon DD for use in WSNs. EAR finds multiple routes, if any, from source to sink nodes, and each route is assigned a probability of being selected to transmit a packet based on residual energy and the energy for communications at the nodes along the route. Then, based on these probabilities, one of the candidate routes is chosen to transmit a packet. The probability is proportional to the energy level at each node such that the routes with higher energy are more likely to be selected. EAR protects any route from being selected all the time, thereby preventing energy depletion. The primary goal of EAR is to improve network survivability. To achieve this goal, EAR occasionally uses sub-optimal paths to slow down the depletion of node energy across the network. As a consequence, networks employing EAR will have a longer lifetime than those using algorithms such as DD. However, EAR cannot efficiently reflect current residual energy, because it does not update its neighbors’ forwarding tables while disseminating data.

Multipath routing has been widely studied in wired networking. It is an effective method to alleviate the effects of network congestion and guarantee the QoS provisioning as well [22]. In general, there are two kinds of multipath between two nodes. One is the classical node disjoint multipath, while the other approach abandons the requirement for disjoint paths and instead builds many braided paths (Fig. 3). That is, the braided multipath routing relaxes the requirement for node disjointness, meaning that alternate paths in a braid partially overlay with the primary path and thus are not completely node-disjoint. In reference paper [23], node disjointness and link disjointness are discussed in detail. Furthermore, the authors studied two different approaches about constructing multipath in Ad-hoc network. One is the backup routes for fault tolerance. The backup route is ac-
activated when the current primary route faces a link failure. And the other is data transfer routes for load balancing. In here, multiple routes are simultaneously activated and data packets are distributed over them.

Recently, Lu et al. proposed an Energy-Efficient Multipath Routing Protocol (EEMRP) [17], [18]. EEMRP has the capability of searching multiple node disjoint paths and utilizes a load balancing method to allocate the traffic rate to each selected path. The link cost function introduced in EEMRP takes into account both the node residual energy level and hop count. Furthermore, the level of load balancing over different multipath is evaluated by using a fairness index. EEMRP has three phases: Initialization, Paths search, and Data transmission. In the initialization phase, each node collects the information from neighbor nodes, such as energy level and the related sink information, through a broadcasted HELLO message. When a HELLO message arrives, and if it is received for the first time, each node will update its neighbor node table. Figure 7 shows a HELLO message being flooded through an entire sensor network. The numbers mean the ordering of the event sequences, in Fig. 7 and Fig. 8. We implemented EMRA using JAVA to demonstrate this principle. Finally, in the sink node, the HELLO message is rebroadcasted with the cumulative distance from the sink node, as depicted in Fig. 8. The distance from the sink node to current node is stored in the cumulated distance field of HELLO message. Initially, the value is 0 in the sink node. In the next subsection, this value will be denoted by $d(x, z)$ where, $x$ is the current node and $z$ is the sink node. Each node may have the neighboring node table updated at the end of this phase.

3. An Energy-Aware Multipath Routing Algorithm (EMRA)

In this paper, the proposed multipath routing protocol, Energy-aware Multipath Routing Algorithm (EMRA), is designed to use only the localized information to find node-disjoint paths between a pair of source and sink nodes in WSNs. In order to increase sensor node lifetime, decrease average energy consumption, and reduce delay time, EMRA simultaneously takes into account the node residual energy level, the effective transmission radius, and the real distance from a sink node.

As depicted in Fig. 4 [20], when an event occurs, the surrounding nodes first exchange information and select from among themselves the source node. Here, we assume that the sensor network is connected and dense. Each sensor node can acquire its residual energy level and failure probability and can maintain neighbor node information. EMRA has three phases: Initialization, Multipath search, and Data transmission / maintenance.

3.1 Initialization Phase

The first phase of EMRA is initialization. When a stimulus is detected, a HELLO message is exchanged between nodes. The source node broadcasts the HELLO message throughout the network. As the well-known AODV of Ad-hoc routing protocols [24], the HELLO message acts as a similar role of RREQ. The format of the HELLO message is shown in Fig. 5. The message sequence field is a number generated by the message originator. The HELLO message is indicated by the use of a message type field. The node type field specifies whether the message is from a sink, source, or relay sensor node. The neighbor node ID field contains the upstream node ID that was responsible for forwarding the message in the previous node. The normalized neighbor node energy level and hop-distance fields are written by mentioned assumption. When a HELLO message arrives, and if it is received for the first time, each node will update its neighbor node table. The HELLO message from the sink node is rebroadcasted with the related sink information. At the end of the initialization phase, each node table is also updated. Then each node broadcasts a CONNECTIVITY message to its immediate neighbors. In the paths search phase, the source node unicasts REQUEST message to every neighboring node. Lastly, in the data transmission phase, multiple paths are discovered using a link cost function, and the sink node adjusts traffic flows. However, the link cost function considers an energy factor as only the ratio of the initiation to residual energy and does not take into account a real distance from the sink node, but rather only a hop count from the sink node. Furthermore, the reliability of successful paths is poor, since EEMRP takes care of only data transfer delay.
3.2 Multipath Search Phase

The second phase of EMRA is the Multipath search. To select an appropriate path, EMRA strikes a balance between node lifetime, energy-efficient transmission, and a delay based on three attributes, namely, residual energy, transmission distance, and real distance from the sink node. In Fig. 9, the abscissa axis means normalized residual energy and the ordinate axis means Eq. (1). The logarithm function rapidly decreases the selected probability when the normalized residual energy is low. EMRA is able to select an energy efficient node by using the property of logarithm function. In our simulation, we assume that the logarithm base is 10. Hence, random selection is achieved when the residual normalized energy level is 10%; this value can be regulated. The first factor for a node lifetime is as follows.

$$f_e = \min\{ 1, -\log_{10} \frac{E_{res}}{E_{ini}} \}$$  \hspace{1cm} (1)

where, $E_{res}$ and $E_{ini}$ denote the residual energy and initial energy, respectively.

In our simulation environment, we use the following energy model [21]:

$$E_{tx} = \alpha_1 + \alpha_2 d^n$$  \hspace{1cm} (2)

$$E_{rx} = \alpha_2$$  \hspace{1cm} (3)

where, $E_{tx}$ and $E_{rx}$ denote the energy consumed for transmitting and receiving a bit over a distance $d$, respectively. $\alpha_1$ is the energy/bit consumed by the transmitter electronics. $\alpha_2$ is the energy dissipated in the transmit op-amp and $\alpha_{12}$ is the energy/bit consumed by the receiver electronics. Since $E_{tx}$ increases exponentially with distance when data are transmitted, it may consume less energy when relaying data as opposed to directly transmitting data; however, if the data are relayed too many times, it may consume even more energy. Therefore, determining an ideal distance is important for realizing energy efficient transmission.

Figure 10 shows the data dissemination between nodes $n_0$ and $n_K$. When data are transmitted, the energy consumption through the path $P(n_0, n_K)$ is represented as follows.
We define the average distance between each relay node as \( d \). The optimized number of relay nodes is \( \lfloor D/d \rfloor \), as calculated by \( d \). Therefore, the energy consumption between nodes \( n_0 \) and \( n_K \) is as follows.

\[
E(P(n_0,n_K)) = \sum_{r=1}^{K} E(P(n_{r-1}, n_r))
\]  
(4)

The energy consumption \( E(P(n_0,n_K)) \) is minimized when it has a local minimum value. Therefore, when \( \frac{dE(P(n_0,n_K))}{dd} = 0 \), the value of \( d \) is \( n + \frac{\omega_1}{2(\omega_1 + \omega_2 + \omega_3d^2)} \)  
(5)

The second factor for a transmission distance is as follows.

\[
f_d = \min \{ 1, \frac{|d - d|}{d} \}
\]  
(6)

We have to use the cumulative distance value taken from the distance from the sink field of the HELLO message to select the next hop node. Let us consider the case where a current node is \( x \), a neighbor node is \( y \), and a sink node is \( z \). Let the distances be \( d(x,z) \) and \( d(y,z) \) between each pair nodes. If \( d(x,z) - d(y,z) \) is not positive, then the third factor \( f_d \) for a delay is 1. If this is not the case, we give preference to the node that gives the highest value for \( (d(x,z) - d(y,z))/d(x,z) \). Therefore, \( f_d \) is defined as shown below.

\[
f_d = \begin{cases} 1 & \text{if } d(x,z) - d(y,z) > 0 \\ 1 - \frac{d(x,z) - d(y,z)}{d(x,z)} & \text{otherwise} \end{cases}
\]  
(7)

The measure function \( f_m \) of node \( m \) is as follows.

\[
f_m = \omega_1f_e + \omega_2f_1 + \omega_3f_d
\]  
(8)

where, each \( \omega_i \) is non-negative and \( \sum_i \omega_i = 1 \).

Thus, the source or current node unicasts the REQUEST message to the node that has the minimal value of \( f_m \) for its neighbor node \( (m \in \text{Neighbor nodes set}) \) along with a route ID. The route ID is assigned by the source node to distinguish between different routes. The path cost field is written by accumulating the summation for \( f_e \), i.e., \( \sum_i f_e \). The probability of successfully delivering field is stored by the cumulative multiplication for \( p_e \), i.e., \( \prod_i p_e \). The path \( P_i \) obtains its probability of successfully delivering a message, \( p_i \), at the sink node.

Figures 11 and 12 show that EMRA constructs a multipath outcome when either \( \omega_2 = 1 \) or \( \omega_3 = 1 \). In the case where \( \omega_2 = 1 \), we know that the shape widely broadens, because EMRA considers only an energy efficient transmission radius. However, the shape is sharpened when \( \omega_3 = 1 \), since EMRA uses the real distance from the sink node.

### 3.3 Data Transmission / Maintenance Phase

The third phase of EMRA is Data transmission / maintenance. In this paper, we consider only the node-disjoint multipath, because a braided multipath can easily be transformed into a disjoint multipath. Here, we assume that the sink node obtains \( k \) multiple paths - \( P_1, P_2, \ldots, P_k \) - by receiving one or more REQUEST messages. As Fig. 13 shows, each path \( k \) is a different path, each of which has some rate \( p_i \) (\( i = 1, 2, \ldots, k \)) that corresponds to the probability of successfully delivering a message to the sink. Since each path \( P_i \) has a Bernoulli distribution with parameter \( p_i \) and \( k \) paths are node-disjoint paths, Fig. 13 is corre-
responded to a repeated Bernoulli experiment. Therefore, the expectation for the total number of successful paths is given as follows.

\[ (1-p_1 + 0(1-p_1)) + \cdots + (1-p_k + 0(1-p_k)) = \sum_{i=1}^{k} p_i \]  

(10)

We define \( N_{\text{max}} \) as an upper bound of paths, i.e., \( N_{\text{max}} = \lceil \sum_{i=1}^{k} p_i \rceil \).

EMRA selects the suitable node disjoint paths \( P_1^*, P_2^*, \ldots, P_{N_{\text{max}}}^* \) of \( k \) paths by descending order of the probabilities. EMRA uses the following load balance ratio to evaluate the level of load balancing over different multi-paths.

\[ \frac{1}{C_1} : \frac{1}{C_2} : \cdots : \frac{1}{C_{N_{\text{max}}}} \]  

(11)

where, each \( C_i \) is the final value in the path cost field of RE-QUEST messages. The sink node then informs the source node of these traffic flows with ACK messages.

4. Performance Evaluation

We implemented the proposed protocol EMRA using C++ to evaluate its performance and compare it with DD and EEMRP. We adopted the IEEE 802.11 MAC layer. The main parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Simulation variables.</th>
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<tr>
<td>Network size</td>
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<td>Transmission range</td>
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<tr>
<td>Data packet size</td>
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<td>Control packet size</td>
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<td>Transmission rate</td>
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<td>Transmitted total data</td>
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<td>Energy consumption model ( E_{tx} )</td>
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<td>Energy consumption model ( E_{rx} )</td>
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<td>( a_{11}, a_{12} )</td>
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Figure 14 shows a sample network where the node density is \( 250/160^2 = 0.01 \) nodes/m\(^2\). In our simulation, the positions of the source and sink nodes were located far from each other, and we assumed that EMRA had the same weight \( \omega_i = 1/3 \) throughout.

The node energy consumption measures the average energy dissipated by the node to transmit a data packet from the source and sink nodes. As shown in Fig. 15, EMRA outperformed EEMRP by 6.1~27.0%. The reason for this was that EMRA generated fewer control messages than EEMRP.

Figure 14 An example for simulation sensor network.
In addition, DD was the most costly protocol.

The control message overhead is obtained by calculating the ratio between the average number of control messages processed by the node and the number of data packets received by the sinks. Since DD requires periodic interest broadcast and path reinforcement, the value was very high,
as shown Fig. 16. There are essentially no CONNECTIVITY messages in EMRA, thus giving EMRA an overall performance improvement of 38.1–56.8% over EEMRP.

As shown in Fig. 17, multipath routing protocols have the shortest delay compared to DD; however, the delay values of EMRA and EEMRP are similar. We assumed that each node has a probability of failure, as would be expected in a real environment. Additionally, the given network area was enlarged from 160 m x 160 m to 320 m x 320 m, thus allowing us to observe the delay in terms of the transmission range. As depicted in Fig. 18, delays in EMRA were always shorter than EEMRP. If the transmission range is large, then we are thinking more disjoint paths than the case of small range. There may be not only several paths of high successful probability, but also lots of paths of low successful probability. Since EEMRP does not take network reliability into consideration, EEMRP suffers from average delay than EMRA. In reference paper [25], the authors proposed Expected Transmission Count (ETX) metric on multi-hop wireless networks. ETX is to choose routes with high end-to-end throughput as considering the distribution of link loss ratios. The delay of EMRA during the load balancing, in particular, is shorter when the transmission range is large, which is due to the fact that EMRA selects paths that have a high probability of successfully delivering a message like ETX.

Figure 19 (a) shows failure ratio which is the number of failures to the total data transmission number. As from transmission range 80, the failure ratio of EMRA is substantially different from that of EEMRP. The reason is that EMRA is able to choose the paths of high successful probability as mentioned above like Fig. 18. In addition, performance for throughput is described in Fig. 19 (b). The throughput is then calculated by dividing the file size (40960 bits in this simulation) by the transmitted time. Since the failure rate of EEMRP is increasing as from transmission range 110 as shown in Fig. 19 (a), the throughput of EEMRP is also decreasing as shown in Fig. 19 (b).

5. Conclusion

This paper describes the various routing algorithms currently used to achieve energy efficiency in wireless sensor networks. In addition, we studied fault tolerance and load balancing mechanisms based on multipath. We proposed a new protocol, the Energy-aware Multipath Routing Algorithm (EMRA), which is a distributed, scalable, and localized multipath algorithm to discover node disjoint paths between the source and the sink nodes. Furthermore, a load balancing algorithm was proposed to distribute traffic over the multiple paths discovered, taking into consideration network reliability. Various computer simulations showed that EMRA had a higher node energy efficiency, lower control overhead, and shorter average delay than those of well-known previous works. One of the interesting aspects of this paper was that we considered network reliability, because failures in a network will undoubtedly arise. Hence, EMRA is useful for delivering data in unreliable environments. In future studies, we will consider extending some of this algorithm to source and sink mobility.

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