An Online Multipath Routing Algorithm for Maximizing Lifetime in Wireless Sensor Networks

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Abstract

We address the maximum lifetime routing problem in wireless sensor networks, and present an online multipath routing algorithm. The proposed algorithm strives to maximize the network lifetime metric by distributing the source-to-sink traffic for a given routing request along a set of paths. Fuzzy membership function is used for designing the edge weight function. Simulation results obtained under a variety of network scenarios show that the proposed multipath scheme is able to achieve better lifetime results than those obtained by its predecessor single-path fuzzy routing scheme as well as by another well-known online routing scheme, namely the Online Maximum Lifetime heuristic.

Keywords: Wireless sensor networks, lifetime maximization, multipath routing, online routing, fuzzy membership functions.

1. Introduction

Wireless sensor networks (WSNs) offer a number of useful application in various fields [1,6]. The sensor nodes used in many cases are powered by battery sources, and there are numerous sensing applications where the these nodes are deployed in a huge number in a remote environment. Due to all these facts, the importance of energy conservation in WSN has long been established, and a large number of lifetime maximization routing techniques have been proposed [2, 6, 19]. A brief review of the related work is presented in Section 2.

The existing routing schemes, based on their working mechanism, may broadly be divided into the offline and the online routing schemes. An online routing algorithm tries to find the best path for each routing request without the knowledge of the future routing requests [18]. A routing request is initiated by a sensor node, at any instance of time, to indicate its intention to send its sensed data to one of the sink nodes. Further, an online routing algorithm makes no assumptions about data rates at the source node. On the other hand, an offline routing algorithm usually requires full knowledge of all the future routing requests. Moreover, a number of existing offline routing algorithms assume that only a prefixed node (or a subset of nodes) in the entire network may act as source node(s), and that their data generation rates are known a priori. Although an offline routing model may suit certain WSN applications, we believe there are numerous WSN scenarios, where an online routing model captures the event-driven WSN nature more accurately - an event may occur at any location at any point in time, and any node detecting the event may start acting as a source node. Section 4 describes the system model, and formulates the online routing problem.

We present an online multipath routing scheme, namely the fuzzy multipath maximum lifetime routing scheme (FML-MP) that maximizes the network lifetime by striving to achieve a good distribution of the source-to-sink traffic along a set of paths. The proposed FML-MP scheme is a multipath extension to our earlier work, namely the fuzzy maximum lifetime (FML) routing scheme [16]. Like FML, the path search process in the proposed FML-MP algorithm is also based on the use of an edge-weight function designed by using a fuzzy membership function [24, 25] (A short introduction to fuzzy membership functions is given in Section 3). Section 5 presents the details of the proposed multipath routing scheme.

There are a number of strong motivations for designing a multipath routing scheme: First, the multipath routing schemes have been a popular choice in the context of energy-aware routing in WSNs [2, 19]. A reason for this trend is to exploit the beneficial feature of the multipath routing approaches that, for a given routing request, these schemes try to distribute the source-to-sink traffic among multiple paths. Second, since the FML routing scheme [16] was able to obtain the lifetime values that were consider-
ably better than those obtained by the two well-known online routing schemes, namely the online maximum lifetime heuristic (OML) [18] and the CMAX heuristic [12], therefore it seems interesting to investigate whether any further performance gains in terms of the network lifetime may be obtained by its multipath extension.

We compare the proposed multipath algorithm to its single-path predecessor, the FML routing scheme [16] as well as the OML heuristic. Simulation results indicate that the multipath FML-MP scheme is able to achieve longer lifetimes than those obtained by the other two schemes. Performance evaluations and discussions are given in Section 6, and some concluding remarks are stated in Section 7.

2. Related Work

Comprehensive reviews of existing routing techniques for WSNs are given by Al-Karaki and Kamal [2], and by Perillo et al. [19]. Al-Karaki and Kamal classified the existing routing schemes into may categories based on network structure (hierarchical or flat) and protocol operation (such as negotiation-based, multipath). For brevity, we just mention pointers to some existing work, and interested readers are referred to our technical report [17] for a relatively detailed account of the literature review.

A number of offline routing solutions based on analytical approaches are found in the literature [3,15,22]. A utility-based scheme for maximum lifetime routing is described by Yi et al. in [5].

Some heuristic-based online routing schemes have been proposed in the past [12,13,18]. Kar et al. presented the CMAX [12] heuristic that proceeds by assigning a weight to each edge in the network using an edge-weight function. Park and Sahni presented the online maximum lifetime heuristic (OML) [18] that is based on an enhanced version of the CMAX edge-weight function. In both the schemes, following the weight assignment step, the minimum weight path is found using the Dijkstra’s shortest path algorithm. The OML heuristic was shown to obtain better results than the CMAX heuristic in terms of the lifetime as well as the energy consumption metric.

Several multipath routing algorithms have been summarized in [2]. The energy aware routing (EAR) [20] due to Rahul et al. is a distributed multipath protocol that discovers and maintains multiple paths with their accumulated costs by local flooding. The best maximum lifetime path is chosen probabilistically based on the accumulated path cost.

Intanagonwiwat et al. [10] proposed directed diffusion scheme that may be classified as a negotiation-based multipath algorithm. In this scheme, the best favorable path is chosen based on the reinforcement messages received along a path from the sink node. A braided path approach, which is a variation of the directed diffusion scheme is suggested by Ganesan et al. [8]. This scheme contrasts from the former in that it does not require the multiple paths to be completely node-disjoint.

Lu et al. present an energy-aware multipath routing protocol [14]. Srinivasan et al. [23] proposed a data-centric routing scheme where a node decides to participate in a packet forwarding task only if it has sufficiently enough residual energy.

3. Fuzzy Logic: An Introduction

Fuzzy Logic is a mathematical discipline invented to express human reasoning in rigorous mathematical notation. Unlike classical reasoning in which, a proposition is either true or false, fuzzy logic establishes approximate truth value of a proposition based on linguistic variables and inference rules. A linguistic variable is a variable whose values are words or sentences in natural or artificial language [25]. By using hedges like ‘more’, ‘many’, ‘few’, and connectors like ‘AND’, ‘OR’, ‘NOT’ with linguistic variables, an expert can form rules, which will govern the approximate reasoning.

In the context of crisp sets, a certain element is either a member or a nonmember of a set (in other words, membership is either 1 or 0), whereas in fuzzy logic, a certain element may have partial membership in a set (membership is in the range [0,1]).

A fuzzy membership function is used to compute the membership corresponding to a given value of a linguistic variable. The membership function can be designed in a flexible way in order to reflect the desired goodness behavior of an objective corresponding to a given value of the variable. For instance, as we shall see in Section 5, we design a fuzzy membership function for computing lifetime membership \( \mu_{lt} \) corresponding to the residual energy value of a node, where a higher value of \( \mu_{lt} \) means a higher goodness level of the ‘lifetime’ objective.

4. The System Model and Problem Formulation

In this section, we present a brief description of our WSN system model, and also formulate the maximum lifetime online routing problem. We consider a static WSN deployment, and model it as a directed graph \( G(V,E) \), where \( V \) is the set of nodes and \( E \) is the set of edges. All the nodes have equal initial energy \( \sigma \). The node batteries are neither replaceable nor remotely rechargeable. Each node \( v_i \in V \) has a set of neighbor nodes (denoted as neighborhood set \( N_i \)) that \( v_i \) can each by a single hop transmission using a certain maximum transmission radius \( r_i \). An edge \( e(v_i,v_j) \) between the two nodes is defined to exist only if \( v_i \) and
are within each others radio transmission range, i.e., if $d_{ij} \leq r_t$ where $d_{ij}$ is the Euclidian distance between the two nodes.

The energy consumption model used in our simulations is based on the first order radio propagation model used by many related works [3,9,11]. According to this model, the energy expended by a sensor node during transmission and reception of a k-bit packet is given by Equations (1) and (2), respectively.

$$TX_{ij} = (A + B \cdot d_{ij}^m) \cdot k$$  (1)
$$RX_{ij} = A \cdot k$$  (2)

where $A$ is distance-independent, and accounts for the energy consumed in running transmitter or receiver circuitry, $B$ denotes the energy required by the transmitter’s amplifier, whereas $m$ is a field constant typically in the range $[2,4]$ and depends on certain characteristics of the wireless medium.

We have a set of source nodes performing sensing task as well as a set of sink nodes (base stations) that receive data from the source nodes. At any time, a source node $v_h$ may initiate a routing request $r_h(v_m,v_n)$, $h = \{1, 2, \cdots \}$, for sending its sensed data to a sink node $v_n$. A routing request does not imply a single data packet, rather it represents a sequence of data packets to be sent from the source node to a sink node. We assume there are numerous routing requests $\{r_1, r_2, r_3, \cdots \}$ during the lifetime of WSN. The goal of the proposed online routing algorithms is to efficiently route each routing request $r_h$, without knowledge of future routing requests $r_q$ (where $q > h$), in such a manner that maximizes the number of successful routing requests before the end of WSN lifetime.

We use a simple, but commonly used, WSN lifetime definition: The WSN lifetime is equal to the minimum of the lifetime values of all the node in the network, i.e., the network lifetime ends as soon as any node in WSN runs out of its battery [3,5,15,22]. If the lifetime of a WSN node is denoted by $T_{v_i}$, the WSN lifetime may be expressed as given by Equation (3).

$$T = \min_i \{T_{v_i}\} \quad \forall \ v_i \in V$$  (3)

5. The Fuzzy Multipath Maximum Lifetime (FML-MP) Routing Scheme

We describe the details of the proposed fuzzy multipath maximum lifetime (FML-MP) routing algorithm. As mentioned earlier, the proposed routing schemes makes use of a fuzzy membership function to compute the values of edge-weights. In order to apply fuzzy logic to the maximum lifetime routing problem, a linguistic variable residual energy of a node $v_i \in V$, and a fuzzy set high lifetime are defined.

The value of a linguistic variable is expressed in words in a natural or an artificial language. A fuzzy membership function is used to map a given value of the linguistic variable to its corresponding membership value in a fuzzy set [24,25]. Unlike crisp sets, in context of fuzzy logic, a certain element may have a partial membership value (in range $[0,1]$). A higher membership value usually reflects a higher goodness level. A membership function can be designed in a flexible way to assign a certain membership value corresponding to a given value of the linguistic variable in order to shape a desired behavior of an optimization objective.

The proposed fuzzy membership function for maximum lifetime (depicted in Figure (1)) to map a value of the variable residual energy to its corresponding fuzzy lifetime membership value $\mu_{v_i}^{\sigma}$ assigns a high membership value to an edge having a large amount of residual energy ($re$) at its starting node $v_i$. Initially, when the residual energy of a node is equal to $\sigma$, each of its outgoing edges is assigned a membership value of 1.0. As the node residual energy decays, the corresponding membership value falls, initially at a slow rate and then at a sharp rate. This behavior of the membership function strongly discourages the inclusion, on the selected routing path, of those intermediate nodes that have depleted their energy beyond a certain threshold value. The threshold point may be altered by adjusting the value of $\alpha$. An expression for the fuzzy lifetime membership function can be derived using the equation of line, and is given by Equation (4).

$$\mu_{v_i}^{\sigma} = \frac{re - re_i}{\alpha \cdot \sigma}$$  (4)
maximum life time path as follows: When a routing request

is assigned to each edge in WSN using Equation (6). Fol-

is computed for each edge using Equation (4), and hence a weight

are found using Dijkstra’s shortest path algorithm [7].

Depending on the WSN topology and node density in a certain region, it is not always feasible to successfully find fully-disjoint paths, therefore we allow braided paths too while minimizing the number of common nodes. Our method of searching π-shortest paths is described as follows: After the first shortest path is searched, the nodes lying on that path are assigned a considerably high weight in order to discourage their inclusion in the subsequent path searches. Thus the path search will only resort to a braided path (i.e., inclusion of any of these already used nodes) when there is absolutely no better alternative available.

To allow further flexibility, π is not a fixed integer, rather it is determined by the path search phase as follows: We define the cumulative weight $W_q$ of a path $p_q^h$ as the sum of the individual weights of the edges lying on the path. The cumulative weight of the first shortest path $W_1$ is used as a reference point. The stopping threshold for the path search phase is $W_1 \times 2$, i.e., if a path is found with $W_q > W_1 \times 2$, we reject that path and search no further.

A roulette-wheel choice is used at the source node to probabilistically allocate a certain fraction of the source-to-sink traffic to a path $p_q^h$. This fraction is inversely proportional to the path’s cumulative weight $W_q$. In this way, a path having an overall lower weight has a higher probability of routing a larger fraction of the traffic.

6. Performance Evaluation and Discussions

Our simulation setup consists of a 2-dimensional grid of size $X \times Y$, populated with randomly deployed $n$ sensor nodes. In our simulations, the sink node(s) are assumed to have infinite energy (powered by a fixed power source) and predetermined location(s), whereas all other nodes (including the source nodes) have an equal level of initial residual energy equal to $\sigma$. In the scope of a routing algorithm, we assume a perfect MAC layer with no energy losses due to retransmission attempts (it may appear to be an optimistic assumption considering the typical contention-based wireless MAC protocols, but some recently proposed MAC protocols are able to offer deterministic, contention-free channel access guarantees [4, 21]).

As described in Section 4, there are a number of simulation parameters to which, we need to assign suitable values. For the wireless medium related parameters $A$, $B$ and $m$, we used typical values as were used by many other works [3, 11]. A list of all the simulation parameters and their values is given in Table 1.

<table>
<thead>
<tr>
<th>$\sigma$</th>
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<tbody>
<tr>
<td>$A$</td>
<td>$100 ; nJ/bit$</td>
</tr>
<tr>
<td>$B$</td>
<td>$50 ; pJ/bit/m^4$</td>
</tr>
<tr>
<td>$m$</td>
<td>$4$</td>
</tr>
<tr>
<td>$X$</td>
<td>$25$</td>
</tr>
<tr>
<td>$Y$</td>
<td>$25$</td>
</tr>
<tr>
<td>$n$</td>
<td>${30, 40, \ldots, 100}$</td>
</tr>
<tr>
<td>$r_t$</td>
<td>${7, 8, \ldots, 15}$</td>
</tr>
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In addition, we have few algorithmic parameters ($\alpha$ and

Table 1. A list of values used for various simulation parameters.

The proposed FML-MP algorithm (Figure 2) finds the maximum life time path as follows: When a routing request $r_h(v_m, v_n)$ is initiated, a fuzzy lifetime membership is computed for each edge using Equation (4), and hence a weight is assigned to each edge in WSN using Equation (6). Following the weight assignment, a set of $\pi$-shortest paths $p_q^h$ (where $\pi \geq 1$ and $q = \{1, 2, \ldots, \pi\}$), between $v_m$ and $v_n$, are found using Dijkstra’s shortest path algorithm [7].
\(\gamma\) for which the best values (e.g., those resulting in the maximum obtained lifetime) must be determined empirically. For this purpose, we experimented with numerous possible combinations of values for \(\alpha \in [0.1, 0.9]\) and \(\gamma \in [0.1, 0.9]\) using various values of \(n\) and \(r_t\). In summary, the overall best value found for \(\gamma\) was 0.9, and hence we used this value for the rest of our simulations. Then, we conducted a series of simulations to determine the best value for \(\alpha\), and based on the results, its value is set at 0.2 for the rest of simulation runs.

6.1. Performance Comparison of the FML-MP Scheme with the FML and the OML Schemes

The primary comparison is between the proposed multipath FML-MP scheme and the FML scheme, but we also include the OML scheme as a baseline reference to see where it stands in comparison to the other two schemes. In case of each routing approach, all the results reported are averaged over 100 runs – 10 random network topologies were generated, and 10 random request sequences were generated for each topology. The performance metric used for comparison is the network lifetime.

![Figure 3](image-url)

**Figure 3.** A comparison of the proposed FML-MP scheme with the FML and the OML schemes in terms of the obtained lifetime for a varying transmission radius \((r_t \in \{7, 8, \cdots, 15\})\) in case of 100-node topologies \((n = 100)\). The FML-MP scheme consistently obtains the highest lifetime values.

We study the effect of transmission radius on the network lifetime. Figure (3) shows the lifetime obtained by the three approaches in case of 100-node topology for a range of values for the transmission radius \(r_t\). It may be observed that the FML-MP scheme consistently obtains better lifetime values than those obtained by the FML and the OML schemes. The lifetime values obtained by all the schemes increase until \(r_t = 12\), and then remain constant. However, as the value of the transmission radius rises, the performance gain of the FML-MP scheme over the other two schemes widens slightly. This trend can be explained as follows: with the increase in the transmission radius \(r_t\), each node is able to communicate farther, and to discover more neighboring nodes, and thus a higher network connectivity is resulted that offers more routing choices at each node. As a result, the FML-MP multipath routing algorithm is able to find a larger number of multiple paths resulting in more cost-effective (maximal lifetime) solutions.

![Figure 4](image-url)

**Figure 4.** A comparison of the FML-MP scheme with the FML and the OML schemes in terms of the obtained network lifetime values for a varying node density \((n \in \{30, 40, \cdots, 100\})\) when \(r_t = 12\). The FML-MP scheme performs better than the other two schemes, and the performance gap is large for the denser topologies.

Next, we study the effect of the sensor node density on the lifetime values by varying the number of nodes \(n \in \{30, 40, \cdots, 100\}\) in a region of fixed size. Figure (4) shows the lifetime values obtained for a varying node density in case of \(r_t = 12\). It may be seen that the FML-MP scheme was able to obtain higher lifetime values than those obtained by any of the other two approaches. Moreover, with the rising node density, the FML-MP scheme shows a sharper increasing trend in the obtained lifetime, and thus the improvement margin of the FML-MP scheme over the FML grows higher. It is a desirable behavior that the FML-MP scheme performs even better for larger network sizes.
7. Conclusions

A multipath maximum lifetime routing scheme is described. The results are promising in terms of the obtained lifetime values. However, we did not conduct a comprehensive set of simulations to study the effects of some important parameters such as multiple sinks or placing the sink nodes at various geographic locations. The proposed scheme is centralized, and thus for a better scalability, a distributed implementation is in progress.

Some possible future directions may include the design of a multiobjective multipath scheme with a view of incorporating other crucial metrics such as the energy consumption and the latency. In addition, we plan to investigate some initial lifetime metrics for WSNs, and to design the corresponding lifetime maximization schemes.

References