Multipath Route Construction Using Cumulative Residual Energy for Wireless Sensor Networks

Saad Rizvi
Electrical and Computer Engineering
University of Manitoba
Winnipeg, Canada
umrizvi@cc.umanitoba.ca

Ken Ferens
Electrical and Computer Engineering
University of Manitoba
Winnipeg, Canada
ferens@ee.umanitoba.ca

***Abstract*— This paper presents a novel method for constructing multiple routing paths based on paths which have highest cumulative residual energy. An advantage of selecting the path with highest cumulative residual energy is that it minimizes the probability that nodes along the path will deplete their energy and thus minimizes path failures in the network. The algorithm incorporates a multipath discovery phase without incurring any overhead by "piggybacking" the cumulative residual energy data to existing reinforcement packets of directed diffusion. The algorithm also updates residual energy at the highest rate supported by the network. Simulations show that the proposed method has lower residual energy variance (38%, 30% less) and longer network lifetime (85%, 32% longer) than basic directed diffusion and a load-balanced directed diffusion version which does not implement multipath routes, respectively.**

Keywords-wireless sensor network; energy efficient; directed diffusion; load balancing; cumulative residual energy; braided multipath; network lifetime.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) (due to their low power operation, ease of deployment) have been used for different applications like environmental monitoring, healthcare applications and target tracking [1]. In wireless sensor networking, design of a suitable routing protocol is challenging. In most of its applications the main goal is to maximize lifetime of the nodes in the network. One approach to this problem is to balance the load among all nodes in the network. Since a battery is the only source of energy nodes have, the challenge is to design an effective routing algorithm keeping in mind the goal of maximizing lifetime of the sensor nodes and balancing the load of nodes network wide. Thus, nodes should consume lower energy and load must be balanced to increase network lifetime.

A load balancing algorithm aims to achieve an energy efficient solution for such networks by balancing the work load equally among the nodes in the network. By judicious use of limited available energy, network life time can be extended to the fullest. By considering the network lifetime as the time the first node in the network fails (dies), with load balancing we can think of all nodes being depleted of energy slowly and uniformly causing all nodes to die nearly at the same time. By doing this, one can lower maintenance cost and improve overall performance.

The proposed algorithm utilizes multiple paths between the sink and source nodes to extend the network lifetime by efficiently balancing the traffic load of nodes within the network. Dynamically switching to best path, for routing data towards the sink, not only helps in load balancing but also allows avoiding network failures that may occur at an early stage. This paper attempts to overcome the problem of limited energy resources and unequal energy distribution across the network by proposing this multiple path energy efficient routing algorithm.

The proposed method can be applied to basic directed diffusion (DD) [2] for a large distributed sensor network. Using the basic DD's reinforcement phase, we find the two best paths that have the highest residual energy without incurring any significant overhead. By simply reinforcing the two high cumulative energy nodes, the sink initializes the path discovery phase. Similarly, the reinforced nodes relay the reinforcement by reinforcing their two highest cumulative energy upstream neighbors. This continues until he reinforcement messages reach a source node. Thus, two paths which have the highest cumulative energy from the source to the sink can be constructed.

This paper presents an efficient approach which considers hop count and cumulative residual energy during the data transmission process. The reinforcement message packet (RMP) contains a "cumulative residual energy" field. Each intermediate node during the reinforcement phase adds its own residual energy to the value in this field. When RMPs find the source, the source selects the path with the highest CRE. The rationale behind selecting the path with high CRE is to select a path to support the goals of load-balancing and fault tolerance. This paper implements a multipath routing strategy and incorporates decision making in the source nodes to select a path to provide resilience against node failures. By doing this it was found that load balancing can also be achieved and network lifetime was extended.

The remaining parts of the paper are organized as follows: Section II discusses related work and identifies the extensions and contributions of this work. Section III gives the details of the methods to improve load balancing and fault tolerance among nodes in the network. Section IV discusses the simulation experiments performed to compare the proposed algorithms with other leading algorithms. Finally, conclusions and future work are given.

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II. RELATED WORK

For a flat network with high density of homogeneous nodes (i.e., all nodes have same capabilities), the problem of energy consumption and unequal load distribution can be resolved using energy efficient routing protocols. Among the classification of flat, query based routing protocols, Directed Diffusion (DD) has gained importance due to its flexibility, fault tolerance and energy efficiency. Although in its basic form the protocol does not guarantee load balancing, but extensions have been made [3] to make it more efficient. The initial work in [2] has provision for multipath routing to provide protection from path failures but it does not discuss detailed implementation. Since the algorithm constructs path with least-delay, an approach to implement multipath routing can be to construct multiple least delay paths. These multiple paths can then be used either for concurrent data transmission or by selecting the best path for transmitting data. Using a least-delay path, it is not feasible to incorporate load-balancing in the network. Since the least-delay path will have a minimum number of nodes between sink and source, the energy will be consumed at a greater rate by the nodes along this path than others and they will die prematurely. In most routing protocols, a single-path routing strategy is used for data transmission which is not robust against node or link failures. Considering characteristics of wireless sensor networks (unreliable wireless links, energy resources) a single-path routing strategy cannot meet the requirements of various applications. A multipath routing strategy is an obvious approach to overcome the shortcomings of a single-path routing strategy.

One of the first works on multipath routing for packet switching networks was done by [4, 5], which they called “dispersity routing”. The goal of their work was to distribute the data over multiple paths rather than concentrating on single paths. Following the same basic idea, recently, a lot of work has been done applying multipath routing in WSNs. In [6], load balancing has been achieved using multipath directed diffusion. The protocol creates multiple disjoint or braided paths for distributing traffic along these paths. The protocol also considers reducing overhead in basic directed diffusion (interests, exploratory data packets) by probabilistically forwarding packets and setting up forwarding threshold parameters. It considers *minimum node energy along a path* and *length of the path* to select a path for routing data. By probabilistic decision, it first utilizes shorter paths with high energy and then switches to longer paths. The paper focuses on load balancing and achieving desired network capacity using several paths, although constructing multipaths will help in making communication more robust against failures. Also, in a multipath routing strategy, paths formed can be braided, i.e., they share nodes with other paths or can be node-disjoint. To setup node-disjoint paths, there is some overhead involved as a node along a currently reinforced path can respond negatively to reinforcement messages, which try to reinforce it for other paths. In Multipath routing, after multiple path selection, data can be transmitted either concurrently along these paths to provide even traffic distribution [6, 7] or using the best path for data transmission and keeping additional paths for fault tolerance purposes [8].

Also, multipath routing has been proposed to combat topological instability (e.g., link failures) due to nodal mobility and changes in the wireless environment [9]. The work in [10] aims to develop multiple node-disjoint paths for robust data delivery. It proposes a deployment strategy that provides robustness to both short and long term node failures in ad hoc networks.

Multipath routing has been employed to improve quality of service (QoS) by reducing delays [11]. An important issue associated with sensor networks is the reliability and security of data [12, 13]. One important use of multipath has been proposed in [12] where the authors have proposed a multipath routing algorithm which delivers messages from the source by maintaining data confidentiality. The algorithm shares a secret message, first by creating its multiple shares, and then by distributing the shares along multiple paths, such that, even if a fewer number of nodes are compromised, the secret message will be secure.

The work proposed in the present paper takes the approach of using high-quality single path for data transmission, as using multiple paths for data dissemination might not be a good idea due to unreliable wireless links and interference between nodes in a dense WSN environment. The main idea behind the proposed method is to provide path resilience (against node failures) along with load balancing by constructing multiple paths using cumulative residual energy. It also incorporates multipath discovery without any overhead, since this approach does not explicitly try to achieve disjoint multipaths.

III. METHODOLOGY AND DESCRIPTION OF STAGES

The proposed method of constructing routing paths using cumulative residual energy was applied on directed diffusion. Before implementing multipath routing in DD, we improved the basic DD by incorporating load-balancing. This was done by updating residual energy values of the nodes, network wide, periodically at a low-rate as well as at a high-rate and by reinforcing nodes based on their residual energy values. The main contribution of this work is to implement multipath routing to improve load-balancing and to minimize path failures so that the network lifetime can be extended.

While various definitions of network lifetime have been used in the literature [14], we decided to define “network lifetime” or the termination of the simulation when the first node fails (dies). This definition seems appropriate for load balancing algorithms, since an ideal load balancing would have all the nodes loose energy at the same rate, so that they all die at the same time.

A. Neighbor Discovery and Interest Propagation

At the beginning, the network enters the neighbor discovery phase, in which each node tries to register its one-hop neighbors within its radio range. After this phase, each node has a *Neighbor_List* in its memory which is used for interest propagation. An ‘Interest’ is a query by the operator which can be diffused into the network at any node. This

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node which initializes interest propagation is called the 'sink'. The sink broadcasts the interest message with its desired event type towards its neighbors. Whenever a node receives an interest message (not received previously from the sending node), it makes a new entry in its 'Interest_Table' along with a gradient for that interest. Each interest in the interest table has an associated '*Gradient_List*', having IDs of nodes which sent the same interest to the current node. The gradient list is used to selectively route back exploratory data packets towards the sink. Interest message also has an 'interval' field, which specifies the data rate for the next event. The proposed method unlike many extensions to DD does not try to reduce overhead (by suppressing interest propagation setting up thresholds) as it maintains original characteristics of DD.

B. Exploratory Data and Energy Updates

Eventually the interest message will reach a node which can serve the sensing task specified in the interest message and this node is called the 'source' node, which will initiate exploratory data (ED) sending process periodically. The period of sending exploratory data is extracted from the interest message. ED is then forwarded from the source towards the sink using established gradients through multiple paths. Exploratory data packets (EDPs) are sent out periodically by the source at a lower frequency compared to interest message propagation. To incorporate load-balancing, this method allows each node to have information about the residual energy values of its neighbors and updates it periodically during each ED propagation phase. This is simply done by piggybacking (including) the residual energy value of the sending node on to its ED packet which is sent out to nodes on its gradient list. When this ED packet is received by a node, it will extract the energy update about the sender, and will store it in its *'Senders_List'* along with its residual energy value. In the basic directed diffusion, only the timestamps of ED senders are recorded and updated. After the ED phase, nodes will be having complete residual energy information about their neighboring nodes.

C. Multipath Discovery using Reinforcements

The proposed method reinforces two best paths at every Reinforcement phase for each interest. The sink initiates the Reinforcement phase after it has complete information about the residual energy values of its neighboring nodes. Sink sends out Reinforcement message packets (RMPs) to two of its nodes having highest residual energy. Reinforcing nodes based on residual energy introduces load-balancing in the network. Each node has an '*RMP_List'* which stores the *rmp_ID, hop_Count, CRE* values for each sender sending an RMP.

The two paths formed in our case can be braided i.e., they can be have common nodes along these paths. We do not use disjoint multipath formation due to overhead involved. The reason for reinforcing two paths is just the energy overhead involved with several paths. As RMPs propagate along reinforced paths, each node appends its residual energy value to the CRE field of an RMP. Eventually, these RMPs will find a source node which will then have information about each path's cumulative residual energy. This CRE for each path will specify the health of the path and source selects the one which has highest cumulative residual energy. By doing this, we can avoid bad paths which can fail any time. Also during RMP propagation, each node adds to the '*hop_Count'* field which is used by the source for estimating energy consumed by the path and updating its CRE during data transmission in between two RMP intervals (described in the next section).

D. Reinforced Data Propagation

Once the source receives reinforcement message packet, it arranges for the reinforced data packet (RDP) to be sent back at a higher rate towards the sink. Source in its RMP_List has information about each path's CRE and number of hops taken (hop_Count). CRE is given by (1):

$$CRE = \sum_{i=1}^{n} R_i \tag{1}$$

The R_i is the node *i's* residual energy along the reinforced path. The source node will select the path with the highest CRE and will forward the reinforced data packet (RDP) using this path. The proposed method piggybacks the residual energy value of the sender node onto the RD packet. This value is extracted by the node receiving the RDP and it will update its Senders_List with this residual energy value for the sender node. In this way, residual energy values are updated across the network at a higher rate compared to slower ED updates. Since the source node does not get any update about the CRE (before the next reinforcement) of the selected path while it's transmitting data through it, it estimates the CRE value of the path in use by simply using the hop count along that path and the energy consumed for transmission. While sending data along a chosen path the source node estimates the CRE using:

$$CRE = CRE - (hop\_Count * tx\_Energy) \tag{2}$$

In case, if source node finds the second path higher in CRE than the one being used, it will route data through this alternate path. By doing this the source can insure that it selects a healthy path every time for data transmission and can switch to another path dynamically if it finds degradation along the used path. With different paths being formed every time during the reinforcement phase and by utilizing the path high in energy resources, the proposed method provides load-balancing along with fault tolerance.

IV. EXPERIMENTAL RESULTS

A Java simulator was developed to simulate the effectiveness of the proposed cumulative residual energy (CRE) for creating multiple paths in directed diffusion. A Java simulator was chosen to enable comparison of the results of this work with previous work done by the authors [3]. Our next step will be to port the preliminary Java-based

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simulations to ns2 for validation and comparison with other work in the field. This will be followed by applying the CRE method to real sensor nodes.

The three variants are referred to as: “Basic DD”, “Load balanced DD with ED & RD energy-piggyback” and “Multipath DD with CRE piggyback”. The network was simulated for different number of nodes from N=300, 400, ..., 600. Initial residual energy for each node was equal to 2×10^4 Joules; radio range = 4 m. The energy consumption by a transmitting node was set to 2 J and 1 J for a receiving node, establishing a ratio of 2:1, as was done in [15]. In the simulations of the proposed CRE method, the ratio of transmission to reception energy consumption was not significantly sensitive to the exact ratio. For instance, the ratio was changed to 1.5:1, and it was found that the net effect on results was almost identical. The event triggering times for interests, exploratory data, reinforcements and reinforced data were 5 s, 10 s, 15 s and 1s respectively.

A. Residual Energy Variance

As we can see from Fig. 1, the proposed method has a lower variance (38%, 30%) in residual energy than that of the basic DD and load balanced DD respectively. By reinforcing paths based on high residual energy, instead of least-delay, and updating residual energy values at a higher opportunistic rate we can improve the energy variance of the basic directed diffusion, as shown by the result of “Load balanced DD with ED & RD energy-piggyback”. However, by using the multipath DD scheme with proposed CRE based route construction we can see a significant improvement in terms of energy variance as well as network lifetime. This is because of the fact that the proposed method “Multipath DD with CRE piggyback” not only has the load-balancing capability which is implemented in a similar way to “Load balanced DD with ED & RD energy-piggyback” scheme but it also has source selective routing in which source tries to identify the high-quality path every time it send reinforced data. By switching traffic across different paths which are discovered every reinforcement phase, the network achieves more load-balancing than the previous improvement along with a measure to minimize node failures.

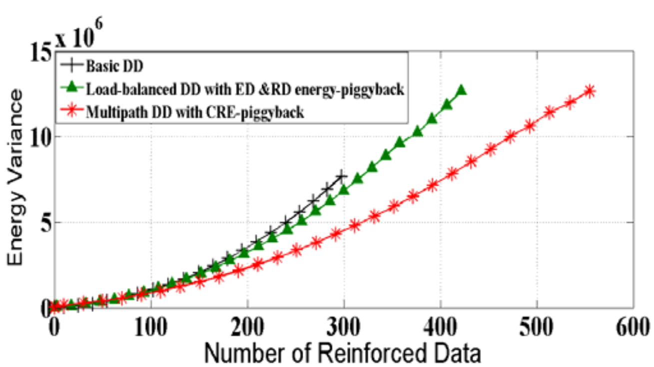

Figure 1. Variance of residual energy vs. average number of reinforced data events generated within the network (for 600 nodes).

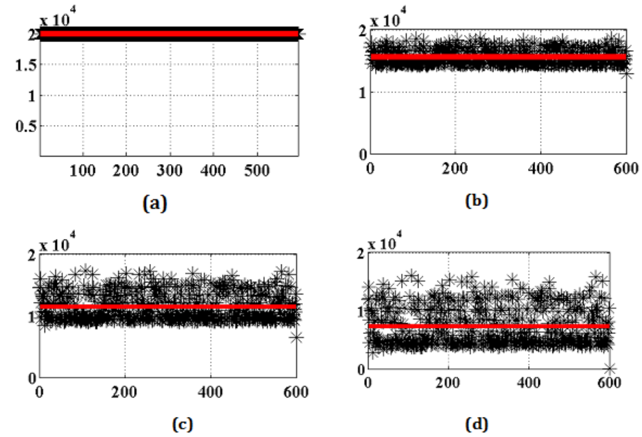

Figure 2. Residual energy and mean residual energy presentation of each node for the basic directed diffusion (four phases of network life).

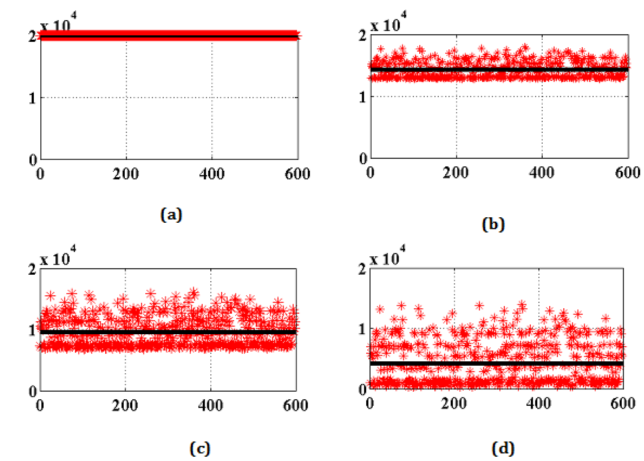

Figure 3. Residual energy and mean residual energy presentation of each node for the Multipath DD with CRE-piggyback (four phases of network life).

B. Load Balancing

In four phases of network life, the network’s residual energy distribution for each node is plotted (before any one node died) for both cases of DD and the proposed multipath DD. Figures 1 and 2 compares the two schemes for 600 nodes. By comparing Fig. 2d (basic DD) with Fig. 3d (proposed method), it is clear that the proposed method was able to live longer by constructing quality paths using CRE, judiciously choosing nodes based on their residual energy and by gracefully lowering the average variance of residual energy near the “death floor” much better than basic DD.

C. Network Lifetime

In Fig. 4, we plot node density versus the number of reinforced data that were passed before any one node in the network died (R_i = 0). It is clear from the figure that the proposed method delivers more RD packets than the basic directed diffusion. The proposed method has a longer network lifetime (85 %, 32%) than the basic directed diffusion and load-balanced directed diffusion respectively.

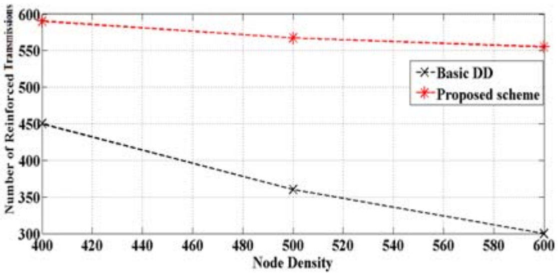

Figure 4. Average number of reinforced data generated within the network vs. number of nodes.

D. Operation

Fig. 5 illustrates the operation of the two main stages (reinforcement and reinforced data propagation) of the CRE method of constructing multiple paths. The Sink node reinforces two nodes with highest residual energy (node X and node Y), which, in turn, will reinforce those upstream nodes having the highest residual energy for any one reinforcement round. Each node along the paths thus formed includes its residual energy when reinforcing its upstream neighbor, and, thus, the cumulative residual energy readings accumulate along the paths. Eventually, the RMPs propagate through two paths and find the Source node. The source node (node Z) will determine the path with the highest cumulative residual energy (CRE1=24800 J), and will select that path for transmitting reinforced data for that reinforcement round. Reinforced data is sent along the selected path till the new reinforcement phase and the CRE value in the source is dynamically updated using (2).

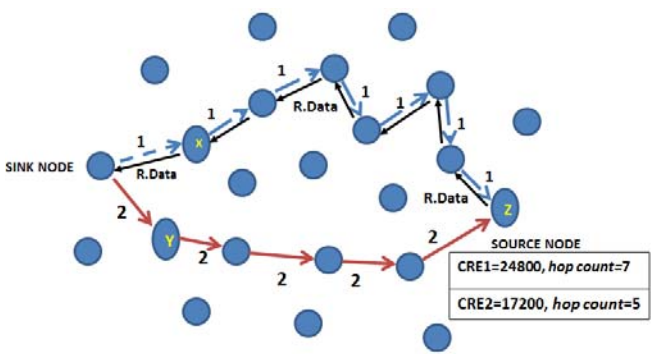

Figure 5. Illustration of the proposed CRE method. The Reinforcement and Reinforced Data propagation stages of the algorithms are shown.

V. CONCLUSION AND FUTURE WORK

This paper presented an energy efficient method of load balancing and fault tolerance for wireless sensor networks. The proposed method constructs multiple paths using cumulative residual energy of the nodes along the path. The proposed method was added to and tested on the Load-balanced Directed Diffusion algorithm [3] to compare its performance. The simulation, analysis, and comparison with load-balanced Directed Diffusion and basic Directed Diffusion show that the proposed method has a lower variance in residual energy and a longer lifetime than both. The proposed method shows 30% improvement in residual energy at the time of network death and an average improvement of 32% in extending the lifetime of the network as compared with load-balanced Directed Diffusion. As compared with Directed Diffusion, the proposed method shows 38% improvement in residual energy at the time of network death and 85% improvement in extending the lifetime of the network.

Our future work includes evaluating multiple sinks and sources to verify its scalability. Also, by simulating the network with patterned failures we can testify its multipath advantage of recovery from bad paths.

A limitation (challenge) of the proposed CRE algorithm is that by considering only residual energy in the path establishment, this increased the latency and delay. The challenge here lies in optimizing the algorithm, so that it can balance between the latency and residual energy to construct optimized paths. Also, the simulation results (Fig. 3d) show that, although the network achieves a good load-balancing; there are still some nodes with high residual energy left, when the network dies. The challenge here is to utilize these nodes and improve load-balancing. Also, work is in progress to implement repair-mechanism to recover from disruptions caused by a node that goes down.

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