Energy Efficient Multipath Routing in Large Scale Sensor Networks with Multiple Sink Nodes

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Abstract. Due to the battery resource constraint, it is a critical issue to save energy in wireless sensor networks, particularly in large sensor networks. One possible solution is to deploy multiple sink nodes simultaneously. In this paper, we propose a protocol called MRMS (Multipath Routing in large scale sensor networks with Multiple Sink nodes) which incorporates multiple sink nodes, a new path cost metric for improving path selection, dynamic cluster maintenance and path switching to improve energy efficiency. MRMS is shown to increase the lifetime of sensor nodes substantially compared to other algorithms based on a series of simulation experiments.

1 Introduction

Recent advance in micro-electromechanical system technology has made it possible to develop low-power and low-cost sensors with at a much reduced cost, so that large wireless sensor networks with thousands of tiny sensors are well within the realm of reality. These large sensor networks are able to support many new applications, including habitat monitoring and agricultural monitoring . In such wireless sensor networks (WSN), sensors send data packets to sink nodes through multi-hop wireless communication. As the size of the network increases, the sensors near the sink nodes will dissipate energy faster than other sensors as they need to forward a larger number of messages, and prolonging the lifetime of whole network becomes a critical problem. One promising approach is to deploy multiple sink nodes in WSN, since it can decrease the energy consumption of sensors and improve the scalability of the networks.

In this paper, we propose a protocol called MRMS, which stands for "Multipath Routing in wireless sensor networks with Multiple Sink nodes". MRMS includes three parts: topology discovery, cluster maintenance and path switching. The topology is constructed based on the TopDisc algorithm [1] using our own path cost metric (which is described in a later section). Next we rotate the cluster head within a cluster and change delivery node between clusters to balance energy consumption in the cluster maintenance process. Finally, when some of the sensors in the original primary path have dissipated too much energy, we re-select the primary path to connect to an alternate sink node. Simulation shows that MRMS can improve energy efficiency significantly.

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The main contributions in our paper are as follows: First, we introduce a new path cost metric which is based on the distance between two neighbor nodes, hop count to sink node and the residual energy of sensor node. This metric is very useful in path selection and improve energy efficiency. Secondly our scheme uses stateless clusters in which all the ordinary sensors in the cluster maintain only the previous hop and corresponding sink. This means the cluster head does not need to maintain information on its children in its cluster, which simplifies cluster maintenance considerably. Finally, we introduce mechanisms for path switching when the energy of the sensors in original primary path has dropped below a certain level. This allows us to distribute energy consumption more evenly among the sensor nodes in the network. By combining these techniques, we are able to construct a strategy that outperforms existing algorithms, as shown in the extensive simulation experiments that we have carried out.

The rest of the paper is organized as follows. A summary of related work is presented in section 2. Section 3 describes the design of the MRMS protocol in detail. The performance of MRMS is examined in Section 4 and compared with other protocols using simulation. The paper concludes with Section 5 where some possible improvements to MRMS are pointed out.

2 Related Work

WSN is an area of much research recently. Since routing is a major issue, a large number of routing protocols such as Direct Diffusion [2] and LEACH [3] have been proposed by researchers [4]. In some of these protocols, cluster-based routing is used to decrease energy consumption, such as in TopDisc [1] and LEACH. However, only a few of these protocols deal explicitly with the multiple sink nodes problem, which is the key focus of our paper. A number of recent papers dealt with the optimal placement of sink nodes in multiple sink sensor networks [5] but do not deal directly with routing issues.

One of the earliest cluster-based routing algorithms is the TopDisc algorithm [1], which is based on the three-color or four color algorithm. TopDisc finds a set of distinguished nodes, using neighborhood information to construct approximate topology of the network. These distinguished nodes logically organize the network in the form of clusters comprised of nodes in their neighborhood. However, TopDisc neither considers the residual energy of sensor networks nor the possibility of path switching.

Dubois-Ferries and Estrin proposed an algorithm based on Voronoi clusters to handle multiple sink nodes [6]. This Voronoi algorithm designates a sink for each cluster to perform data acquisition from sensors in cluster. Each node keeps a record of its closet sink and of the network distance to that sink. A node also re-forwards the message if the distance traversed is equal to closest distance and the message came from the closet sink. A drawback of this algorithm is that it does not consider residual energy of sensor node.

A. Das [7] provides an analytical model of multiple sink nodes. However, it also does not also consider path switching or how to handle excessive energy dissipation among the sensors on the original paths. The Two-Tier Data Dissemination (TTDD) scheme [8] provides data delivery to multiple mobile base stations. However, this scheme requires precise position of the sensor nodes, which may be difficult to attain in many cases. It is also designed primarily for mobile sinks, and is not as efficient when the sink nodes are stationary.

3 The MRMS Algorithm

3.1 System Model

In this section we will present the system model used in our work. First we state our major assumptions. We assume there are multiple sink nodes in the wireless sensor networks, each of which has an infinite amount of energy. Every sensor, whose location is randomly distributed, has the same initial energy and radio range. Both the sensor nodes and the sink nodes are stationary. A perfect MAC layer and error-free communication links are assumed because MRMS focuses on routing algorithm, but no communication is possible once the energy of a sensor node has been depleted. A transceiver exhibits first order radio model characteristics in free space i.e. energy spent in transmitting a bit over a distance d is proportional to d^2.

A wireless sensor networks (WSN) is modeled as a graph G(V, E). where V is the set of all sensor nodes and all sink nodes, E is the set of all links.

$$V = V_{sink} \bigcup V_{sensor}, E = \{(i, j)|i, j \in V\} \tag{1}$$

Every sensor's initial energy is E_{init} and its residual energy is E_{RE}. The path is defined as $\{V_1, V_2, \cdots V_i, V_j, \cdots, S\}$, $V_i, V_j \in V_{sensor}$, $S \in V_{sink}$; the cost is defined as the cost of one link $\langle V_i, V_j \rangle$.

$$Cost_{ij} = \alpha \times d^2 + \beta \tag{2}$$

Now we define the path cost as follows:

$$path\_cost = \sum cost_{ij} \times E_{RE}^{\gamma} \tag{3}$$

where α is the energy/bit consumed by the transmitter electronics, β is energy/bit consumed by the transmitting and receiving signal operation overhead for amplifying, and d is the distance between two sensor nodes,which is based on modern RF technology. γ is the coefficient of residual energy and it is a none-zero negative value. From formula (1) and (2), it is clear that the longer the transmitting distance or the larger the overhead, the higher the cost. So the increase in the hop count between the sensor nodes and sink node will increase path cost. In addition, if the residual energy for each sensor decreases, the path cost will also increase. Hence, after a path has been used excessively, the residual energy of the sensors in the path will decrease, driving up the path cost and triggering the path-switching process. The role of the path cost metric in energy-efficient routing will be shown in greater detail in a later section.

3.2 Details of the MRMS Algorithm

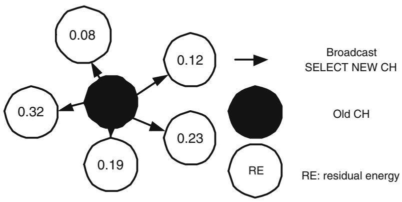
There are three phases in MRMS: topology discovery, cluster maintenance and path switching.

MRMS Topology Discovery Algorithm. MRMS topology discovery is partially based on the three color algorithm used in TopDisc [1], which is derived from the simple greedy log (n)-approximation algorithm for finding the set cover. At the end of the TopDisc topology discovery process, the sensor network is divided into n clusters and each cluster is represented by one node, which is called the cluster head. The cluster head is able to reach all the sensor nodes in the cluster directly because they are all within its communication range. Each cluster head knows its sink, but they can not communication with each other directly. Instead, a delivery node (the grey node) acts as an intermediary which delivers messages between each pair of head node.

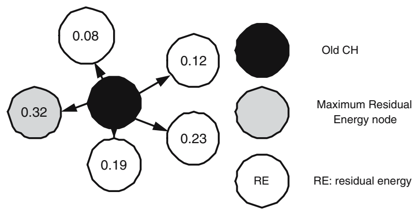
In the MRMS topology discovery mechanism, unlike TopDisc, the cluster is stateless because the cluster head will not maintain any children. Instead every sensor will note its previous hop and corresponding sink in its routing table at the initial topology discovery's broadcast phase, and topology discovery only occurs at the initial phase; this approach reduces the complexity of cluster reconstruction described in the next section. Thus each cluster can be considered a virtual node as far as the topology is concerned. A sensor node may keep information for more than one cluster heads and sinks in the routing table, as it can keep track of different paths from different sink nodes. However only one of these paths can be designated the primary path in the table, and this is the path with the minimum path cost, hence ensuring the topology will be an energy efficient one.

MRMS Cluster Maintenance. As explained in a previous section, MRMS cluster maintenance includes two parts: energy monitoring and cluster reconstruction. Energy monitoring in MRMS is relatively straight-forward. A cluster header will check its energy periodically. If the sensor's residual energy is below some threshold, it will invoke the cluster reconstruction process. A special case is that of a delivery node, in which case it needs to inform its child cluster head to change its delivery node as well.

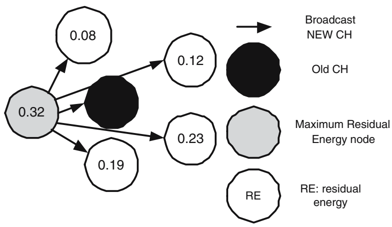
In cluster reconstruction, when the residual energy of the cluster head (CH) is below some threshold, it will broadcast the SELECT_NEW_CH message to its neighbors,when CH can't communicate with other children directly, most of sensors' energy in this cluster has be below some low threshold based on our method, as shown in Figure 1(a). Any sensor that receives this message will checks its routing table and reports its residual energy to the CH if the previous hop in its primary path is the current CH. After combining all incoming information, the current CH will select the child with the maximum residual energy as the new CH and pass control to the new CH, if several nodes have the same maximum residual energy, old CH will select the new CH randomly,as shown in Figure 1(b). The new CH will probe new delivery node based on the path cost, and broadcast the NEW_CH to all its children in its cluster, as shown in



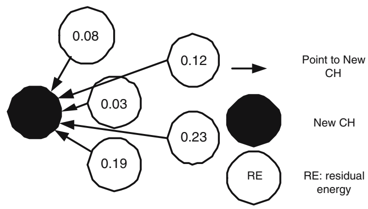
(a) Old CH broadcasts



(b) Selection of node with

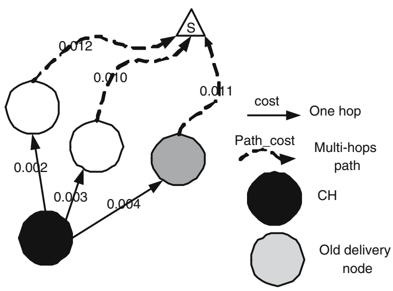


(c) Node with maximum residual energy broadcasts NEW_CH Message to all nodes in the cluster

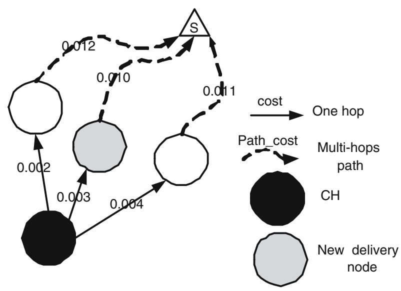


(d) New Cluster after intra-cluster re-construction

Fig. 1. Intra-Cluster Reconstruction



(a) Old delivery node before inter-cluster reconstruction

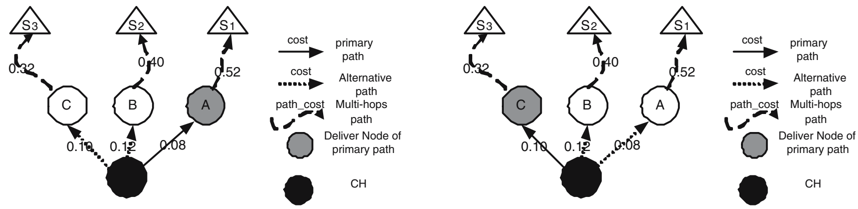


(b) New delivery node after inter-cluster reconstruction

Fig. 2. Changing Delivery Node in Cluster Reconstruction

Figure 1(c), and the result is shown in Figure 1(d). If a sensor node is the delivery node of some cluster head and its residual energy is below some threshold, it will notify these cluster heads to change their delivery nodes, as shown in Figure 2.

MRMS Path Switching. As discussed in a previous section, when the path to the original sink has been used for an extended period of time, there is a need to switch to another sink. There is a problem in determining the suitable sink, however, is that the value of the path cost is not always current. Although it is possible to have use a periodical update approach to refresh the path cost, this technique is expensive and quite unnecessary since switching to a different sink does not occur frequently for stationary sensors. In MRMS, we use an



(a) Primary path before path switching

(b) Primary path after path switching

Fig. 3. Path switching in different sink node

event-based approach where path switching is triggered when during the cluster reconstruction process it is discovered that the current path is no longer the best path.

We will now describe the details of path switching in MRMS, using Figure 3 to illustrate the process. In the original path, because the sensor nodes which are near the sink node consume energy more rapidly than the sensor nodes which are far away from the sink node, these nodes close to the sink will invoke cluster-reconstruction. For example, in Figure 3, sensor A will probably see many of its upstream nodes invoke cluster reconstruction first. Since the path cost in the primary path will be updated whenever cluster reconstruction occurs, there is no need for sensor A to do anything explicitly to refresh the path cost in the primary path ($\{CH \rightarrow A \rightarrow S1\}$ in Figure 3(a)).

However, if in due time the cluster containing A undergoes cluster reconstruction, then there is a possibility that a new primary path will be chosen. The first task is to determine whether there is a need to refresh the path cost to the alternate path, which has not been updated for quite a while. The approach we have adopted is for the source CH to send a probe message to confirm another sink only if the path cost in the original primary path exceeds the path cost in the alternate path by a certain threshold η. The value of this threshold is dependent on the hop count of the CH to the sink, since the larger the hop count, the further away it is from the sink and the larger the interval between cluster reconstruction – and hence the more outdated the path cost of the alternate path is likely to be Figure 3(b) shows the CH sending a probing message to sink S_3 after the above condition has been met. After S3 has received the probing message, it will compare current path cost ($path\_cost_{CH \rightarrow S_3}$) to the original one ($path\_cost_{CH \rightarrow S_1}$). If the current path cost is larger than some threshold, the sink node will send fresh message to all sensor nodes in this path, and if the new calculated path cost in the new sink is less than the path cost of the original primary path, which is the case in Figure 3(a), then source CH will switch to the new sink node, otherwise S_3 will simply return its later path cost to the CH. Either way, the path cost will be broadcast by the CH to all its children in the cluster, and each child sensor node will update its routing table entries accordingly. In case the CH does not receive a reply from S_3, then topology discovery will be invoked again.

4 Performance Evaluation and Simulation Result

To evaluate the performance of the MRMS Algorithm, we have implemented it in GloMoSim [9] which is based on Parsec [10]. In our simulation, we assume the energy model is based on first order radio model in free space, that is, the energy dissipation is:

$$e^T(d) = (\alpha \times d^2 + \beta) \times r$$

where α, β are real numbers. α is the energy consumed at the output transmitter antenna for transmitting one meter, β is the overhead energy representing the sum of the receiver, sensing and computation energy which is independent of the distance d; r is the number of bits transmitted.

In our simulation, the sensor network consists of 250 nodes which are distributed randomly over a planar square region of 100m by100m. There are up to 3 sink nodes, with positions (33.33, 33.33), (66.67, 33.33), (50.00, 66.67). The initial battery capacity of the sensors is set as 0.5J, α is set to 0.1 $nJ/bit/m^2$ and β set to 50 nJ/bit [3]. There are 10 stimulus which generate data flow randomly in simulation, and the position of stimulus is random. And the sensor whose distance to stimulus in 10m can receive the data flow. The data flow is based on Poisson distribution model with an arrival rate of 0.5 packet per second. The data packet size is 2000 bits and all control packets size is assumed to be 100 bits. We set up the simulation time to range from 10 to 150 minutes for evaluating the performance of the various protocols.

4.1 Performance Criteria

The main objective of our simulation is to evaluate the energy efficiency and the lifetime of sensor networks. However, researchers have proposed different definitions of lifetime. In our experiments, we use the following metrics.

- Time to first node failures: This metric indicate the duration for which the sensor network is fully functional i.e. no sensor failure due to battery outage.
- Number of dead nodes: We measure the number of dead nodes as time goes on; this metric provides an indication of the expected lifetime and the reliability of sensor networks.
- Mean Energy Consumption of one packet: the metric indicates the energy consumption of transmitting a packet to sink successfully.
- Average hop count to sink: This metric is useful since the larger the number of hops a packet has to traverse before it reaches the sink, the higher the aggregate energy consumption.
- Packet delivery ratio: this metric is defined as a ratio of the number of received packets at the sink to the number of packets transmitted by the source sensors. The higher the delivery ratio, the higher the reliability of the network. Uneven energy consumption in the network will lead to premature failure of sensors and reduced reliability, hence the packet delivery ratio is also a good indirect measure of the lifetime of the network.

4.2 Experiments and Result Analysis

In this section we discuss the performance of MRMS with the Voronoi Algorithm [6], TopDisc Algorithm and Direct Flooding algorithm. The Direct Flooding algorithm is a simplistic algorithm used as a base case; in its topology discovery phase the sink node simply floods its information to its neighbor sensor nodes without any optimization. After receiving the topology discovery request, the sensor nodes broadcast it again directly without any attempt to optimize the process. Similarly there is no optimization for sending packets to sink nodes. A single sink is used for Direct Flooding.

From Figure 4, we see that MRMS outperforms other protocols significantly, with MRMS close to doubling or tripling the time to first sensor node failure in some cases. In Direct Flooding, the first node dies quicker than the other protocols, because all packets are sent to only one sink and there is no cluster reconstruction and path switching. The TopDisc Algorithm uses clustering to decrease energy consumption which can improve the lifetime of sensor nodes and the Voronoi Algorithm uses the multiple sink nodes which improve the load-balance of data which is sent to sink nodes. However, MRMS by combining multiple sink nodes, cluster reconstruction and path switching, can best balance sensor energy consumption and prolong the duration for sensor network which is fully functional.

From Figure 5, it can be seen once again that MRMS decreases the number of dead nodes significantly, indicating that MRMS is indeed more energy-efficient than the other algorithms. The same conclusion can be reached by looking at Figure 7, which displays the average hop count to sink node for the various algorithms. The effect of using multiple sink nodes is seen clearly in this experiment, as both MRMS and Voronoi Algorithm decrease the hop counts by 1.5-2 hops compared to the Direct Flooding and the TopDisc algorithm. This result is quite obvious since multiple sink nodes will decrease the average distance from the sensor nodes to sink node and hence the hop count will drop accordingly.

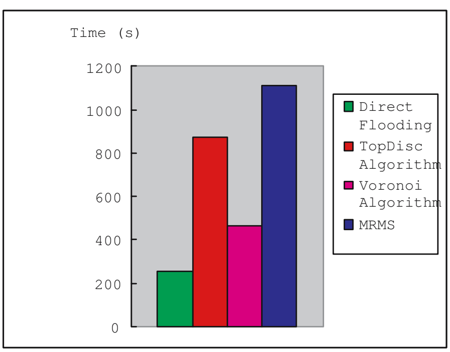


Fig. 4. Time to First Node Failure

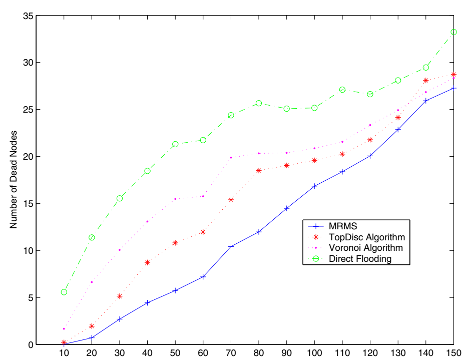


Fig. 5. Number of Dead Nodes

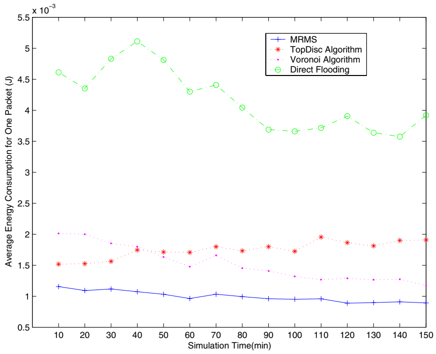


Fig. 6. Average Energy Consumption for packet

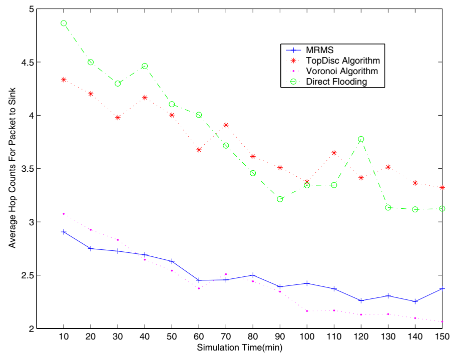


Fig. 7. Average Hop Count vs Time

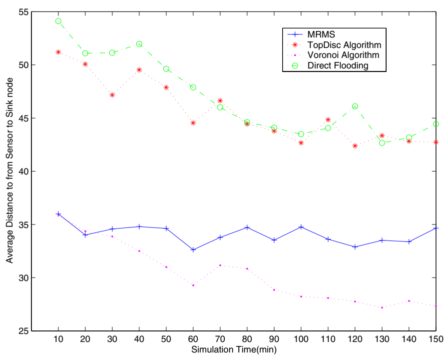


Fig. 8. Average Distance to Sink vs Time

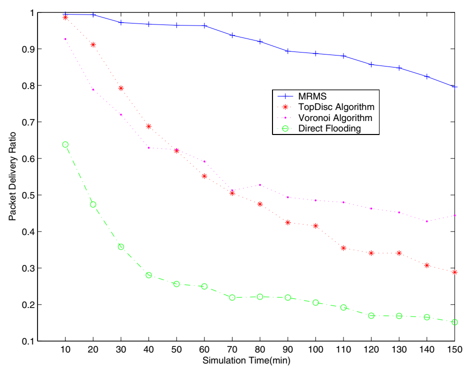


Fig. 9. Packet Delivery Ratio

From Figure 6, it can be seen that MRMS decreases the energy consumption considerably compared with the Voronoi algorithm, TopDisc algorithm and Direct Flooding. As simulation time increases, the average energy consumption for one packet in MRMS and the other algorithms remain relatively stable. There are actually several factors at work. With path switching and cluster reconstruction, the average hop count decreases (as seen in Figure 7). However, the actual distance from (which greatly affects the energy consumption of the packet, as seen in Figure 8) may stay relatively the same because with some of the original best paths no longer available, more and more of the outlying sensors becomes unreachable meaning that the remaining sensors tend to be closer to the sink nodes. Figure 9, shows that MRMS outperforms significantly the other three algorithms significantly based on the packet delivery ratio, indicating the MRMS is indeed more energy efficient and reliable, since most of the packets are actually able to reach the final destination, unlike the other algorithms.

5 Conclusion and Future Work

In this chapter, we proposed the MRMS algorithm which includes topology discovery, cluster maintenance and path switching. Since MRMS uses multiple sink nodes, cluster maintenance and path switching which can distribute the energy consumption in sensor networks more evenly, it enjoys significant improvement in key metrics compared to other approaches. We plan on exploring the effect of a lossy MAC layer on the MRMS, as well as how to construct node-disjoint multipaths for multiple sink nodes.

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