An Energy-Efficient Distributed Routing Protocol for Wireless Sensor Networks with Mobile Sinks

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Abstract. Mobile sink(s) can solve the hotspot issue in static wireless sensor networks (WSNs) but also cause frequent change of network topology, increase the network overhead, and thus affect the network performance. A lot of work has been done to enable efficient routing in such networks. However, little work has addressed the issue of energy efficient distributed routing in WSNs with mobile sinks (mWSNs). This paper designs an energy-efficient distributed routing protocol, which combines energy-efficient data-driven packet forwarding, trail based forwarding, and energy-efficient random walk routing, in order to achieve prolonged network lifetime performance. Detailed protocol design is presented. Simulation results show that our designed protocol can prolong the network lifetime remarkably while maintaining high packet delivery ratio performance with low protocol overhead.

Keywords: Wireless sensor networks · Mobile sinks · Energy-efficient routing

1 Introduction

Wireless sensor network with mobile sinks are often referred to as mWSN and has been a widely used sensing paradigm because mWSNs can relieve hotspot issues in static wireless sensor networks. Much work [1–3] has been carried out in the field of mWSNs, which shows that introduction of mobile sinks can significantly increase network performance. However, in mWSNs, sensor nodes typically have limited resources, and also the mobility of sink nodes brings great challenge to the design of efficient distributed routing protocols for such networks due to the unpredictable

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changes of network topology caused by sink mobility. Therefore, designing efficient routing protocols for mWSN networks has been an important issue to obtain high network performance while yielding light protocol overhead.

A lot of work has been done to enable efficient routing for mWSNs. Existing work in this aspect can be further categorized into the following four types [1–3]: Location based routing protocols, topology based routing protocols, reactive routing protocols, and energy-aware routing protocols. In location based routing protocols (such as LURP [4], TTDD [5], and ER [6]), each node needs to know node location information to make routing decisions. Specifically, such protocols require each node to have its own location, its neighbors' locations, and locations of packet destinations, which can guide hop-by-hop geographical packet forwarding. However, in many cases it difficult for nodes to get accurate location information, in particular for mobile sinks. Topology based protocols (such as AVRP [7] and MDRP [8]) can identify and maintain topological information to form efficient structure for network routing. They typically can obtain short paths at high protocol overhead. Reactive routing protocols (such as TRAIL [7], DDRP [9], and TBD [10]) can learn/update routing information in a reactive way with little overhead and thus have good performance in terms of packet delivery ratio and protocol overhead. Regarding energy-aware routing for mWSNs, Luo et al. [11] studied the issue of joint mobility scheduling and routing in an mWSN while maximizing the network lifetime while Yu et al. [12] studied how to build a quasi-polar coordinate system on an mWSN to support energy efficient ring-based forwarding in such networks.

This paper designs a distributed energy-efficient reactive routing protocol for mWSNs. The goal is to obtain improved network lifetime with low overhead and also high packet delivery performance. For this purpose, our protocol integrates energy-efficient data-driven packet forwarding, trail based forwarding, and energy-efficient random walk routing. According to the designed protocol, the following metrics are jointly utilized when making decision on next hop selections: route freshness, distance to target sink, residual energy at next hop candidates, and progress made via one-hop forwarding. Detailed protocol design is presented. Simulations are conducted and the results show that our protocol can prolong network lifetime remarkably while keeping high performance with low overhead.

The remainder of this paper is organized as below. Section 2 reviews existing work. Section 3 gives the detailed protocol. Section 4 gives simulation results.

2 Related Work

Existing work can be divided into two types: energy-unaware routing protocols and energy-aware routing protocols. Next, we will introduce typical protocols belonging to either type.

2.1 Energy-Unaware Routing in mWSNs

In this aspect, existing protocols include the following three types: Location based routing protocols, topology based routing protocols, and reactive routing protocols. Next, we will introduce typical protocols belonging to each type.

Location Based Routing Protocols

Location based routing protocols use location information of nodes for next hop selection. Major advantages of such protocols include high scalability, good routing performance, and simplicity. Typical protocols in this type contain LURP (Local Update-Based Routing Protocol) [4] and TTDD (Two-Tier Data Dissemination) [5].

In LURP, each sink node selects a small circular area around it. When it moves inside this area, it only needs to report updated location information to sensor nodes in this area, and packets outside the area need to be routed to this area first via geographical forwarding. When the sink moves outside the circular area, it will disseminate its updated location information to the entire network and further select another circular area around it for local update of its location. In this way, the overhead for location update is greatly reduced. TTDD is for multicast data delivery to multi-mobile-sinks. For such purpose, it builds a grid structure for advertisement purpose (i.e., data source node's packet availability). Packet retrieval and delivery are made along such grid structure.

Topology Based Routing Protocols

Topology based routing protocols actively build and maintain efficient routing paths from sensor nodes to sink nodes and allow data packets to be forwarded to nearby sinks with few hops. Typical protocols in this type include Anchor-based Voronoi-scoping Routing Protocol (AVRP [7]) and Multi-Stage Data Routing Protocol (MDRP [8]).

AVRP uses Voronoi-scoping for network partitioning such that each sensor nodes is likely to report its generated data packet to its nearest sink node. The problem in AVRP is the high overhead for the re-scoping caused by sink mobility. MDRP is an improved version of AVRP. Compared with AVRP, MDRP divides the scope covered by each sink into multiple layers based on hop distance, which largely reduce the frequency of wide-area topological update. Topology based routing protocols are suitable for moderate or heavily loaded mWSNs. Usually, establishing and maintaining efficient routing structure in an mWSN can cause a large amount of protocol overhead.

Reactive Routing Protocols

Reactive routing protocols can learn or update routing information adaptively. This type of protocols usually (e.g., TRAIL [7], DDRP [9] and TBD [10]) has low overhead but long route acquisition latency and is suitable for mWSNs with light traffic load.

TRAIL integrates trail-based forwarding and random walk. As a sink moves in the network, it needs to keep broadcasting beacon messages in order to leave a trail behind it. When having a data packet to report, trail based forwarding has priority to be taken, otherwise random walk routing is performed. TRAIL is suitable for dense WSNs such that trail break rarely happens. In the DDRP protocol, data packet carries an extra option in its IP packet header, in order to record the distance between the packet sender and a target sink. Sensor nodes work in promiscuous mode to learn and update local routing table via overhearing of data packet transmissions in the neighborhood. Accordingly, DDRP largely reduces the overhead for route updating and learning. TBD combines data-driven route learning/updating and trail based forwarding for improved routing performance. When a sensor node has a data packet to forward, the priorities of different routing strategies in DDRP (from the highest to the lowest) is as follows: trail-based forwarding, data-driven routing, and random walk. Simulation results show that TBD outperforms DDRP and TRAIL.

2.2 Energy-Aware Routing in WSNs

Energy-aware routing has been a critical issue in WSNs [13] and much work has been done in this area. Next, we shall briefly introduce typical work in this area.

The LEACH-C protocol [14] extends the well-known LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol [15]. In these two protocols, sensor nodes are organized into a two-tier clustering regime such that a number of cluster head nodes are elected, which are responsible for communicating with base station while other regular nodes communicate with their cluster head nodes. Such elections work in a round-by-round manner. LEACH-C extends the basic LEACH protocol in the following two ways: node residual energy is considered into cluster head election and desired number of cluster heads are selected in each round. However, LEACH requires each node can directly communicate with the base station, which makes it unsuitable for large-scale WSNs. The MCBCR protocol (Efficient Minimum-Cost Bandwidth-Constrained Routing) [16] is a efficient scalable, and simple solution for mini-cost routing in wireless sensor networks and it identifies proper routes from sensors to sinks while ensuring that assigned load on each edge does not exceed the link capacity. However, operation of MCBCR needs global state information, which has the scalability issue.

There are also some energy-aware hop-by-hop routing protocols for WSNs. In [17], the authors designed an on-demand maximum residual energy routing protocol, which selects the path connecting a source-destination pair but with the maximum residual energy at intermediate nodes on the path. This protocol, however, leads to multiple search rounds for route acquisition. In [18], an energy-efficient geographical forwarding algorithm was presented, which chooses the best choice of next hop based on local network state (including local topology, state of links & nodes on the local topology). However, none of the above work considered how to enable energy-efficient routing in mWSNs, which is the focus of this paper.

There have been some work studying how to prolonging the network lifetime of mWSNs. In [11], Luo and Hubaux studied the issue of joint mobility scheduling and routing in an mWSN while maximizing the network lifetime. Paper [11] presented a generic optimization framework and proved it to be NP-hard. They first proposed an approximate algorithm for the single sink case, and then, they proposed a polynomial approximation algorithm for the general problem. In [12], Yu et al. first built multi-ring based structure in a WSN, which is actually a quasi-polar coordinate system, based on which energy-efficient ring-based forwarding is enabled for packet delivery. Different from the work in [12], in this paper, we shall introduce energy-efficient next hop selection into the joint design of trail based forwarding in TRAIL [7] and data-driven packet forwarding in DDRP [9], in order to achieve prolonged network lifetime while keeping protocol simplicity and robustness.

Our protocol in this paper is an energy-efficient enhancement of TBD, referred to as E-TBD, in order to prolong the network lifetime. Next, we shall present the design details of E-TBD.

3 E-TBD

This section presents the design details of our E-TBD protocol, which combines energy-efficient trail based forwarding, data-driven packet forwarding, and energy-efficient random walk routing for supporting energy-efficient packet forwarding. E-TBD is designed based on the following assumptions: All sensor nodes and sink nodes have omnidirectional antennas and also the same communication range, and no location information is assumed to be known.

Next, we will first give a brief review of TBD, and then give an overview about how our E-TBD protocol works, finally, we give the design details of E-TBD.

3.1 Brief Review of TBD

TBD is a reactive routing protocol such that it learns/updates routing information in a reactive way. TBD combines data-driven route learning/updating, trail based forwarding, and random walk routing. Next, we introduce how the route learning/updating and data packet forwarding in TBD work, respectively.

In TBD, each node has at most two routing entries, one for data forwarding and another for backup. The information in an entry includes the time instant when the route was generated, the distance to the target sink, the identification of the next-hop to target sink, etc. In TBD, each sink node periodically issues beacon messages to its direct neighbors as it moves, which can then learn that they are on the trail of a mobile sink. Regarding data-driven route learning, sensor nodes work in promiscuous mode to learn new routing information to reach mobile sinks via overhearing of transmissions of data packets in the neighborhood.

In TBD, for forwarding a data packet in the network, the priorities of different forwarding strategies are as follows: trail based forwarding, data-driven forwarding, and random walk. Specifically, when a sensor node receives a data packet, it will look up its own routing entries. If it is on a fresh trail, the packet will be forwarded along the trail (i.e., sending the packet to the neighbor sensor node on the trail, which has the freshest sink-related record), otherwise if it has valid routing entry in its routing cache as obtained via overhearing of neighbors' data transmission(s), the packet will be forwarded according to the corresponding entry (data-driven forwarding), otherwise it has no any routing information, random walk will be triggered.

However, design of the TBD protocol had not considered energy use efficiency at sensor nodes, which may lead to reduced energy efficiency and thus shortened network lifetime.

3.2 E-TBD Overview

To obtain high performance, E-TBD combines energy efficient trail-driven forwarding, data-driven forwarding, and energy efficient random walk routing. Energy efficient trail based forwarding makes use of the trail left by mobile sinks, at the same time, maximally prevent nodes with less residual energy from serving as forwarding nodes. Data-driven forwarding makes use of the routing information learnt via overhearing of neighbors' packet transmissions. Energy efficient random walk routing takes the residual energy of neighbor nodes into consideration when making decisions on next hop selection.

3.3 Detailed Design of E-TBD

In this subsection, we will first give how the route learning/updating in E-TBD works, and then present how the data packet forwarding in E-TBD works.

Route Learning/Updating

In the initial stage, all network nodes have no information about how to reach a sink node. When a mobile sink moves, it keeps broadcasting beacon packets to its direct neighbors, which will leave a trail behind the mobile sink. When a sensor node receives such a beacon packet, it will extract the following information from the packet:

(1) Time_stamp, which records the time when the beacon was generated,
(2) Sink_ID, which records the ID of the sink that generated this beacon.

As a sink moves in the network, the sensor nodes which receive such beacon messages can learn/update their routing tables and accordingly form a sink trail.

Meanwhile, sensors in the network can also learn or update routing table in a data-driven way. Specially, for each data packet, it contains the following extra options:

(1) Dist2mSink, which is the so far shortest distance from the sender of the packet to target sink.
(2) Time_stamp, which is the time when an entry was created. More exactly, its value equals the time when the beacon message, which triggers the construction of this route, was issued by the mobile sink.
(3) Sender_ID, which records the ID of the packet sender.

All the neighbors of the sender work in promiscuous mode and can overhear the transmission of such packet and can also extract the above information from the overheard packet. If the Time_stamp extracted from the overheard packet is fresher than the time_stamp recorded at the listening node's routing table, the routing table at the latter will be updated. Progressive route-learning among nodes in the network will let more and more network nodes learn fresh routes to mobile sinks.

Data Packet Forwarding

E-TBD combines energy-efficient data-driven packet forwarding, trail based forwarding, and energy-efficient random walk, and in descending priorities. For a sensor u, when it receives a data packet from the application layer or from a neighbor sensor node, it will look up its local routing entries, and make the following operation for packet forwarding. Specially, if it has fresh sink trail information, then perform energy efficient trail based forwarding; else if data-driven routing is applicable, then perform data-driven routing; otherwise, perform energy efficient random walk routing. Next, we will introduce how each of these processes works.

(A) *Energy-efficient trail-based forwarding*

In this case, sensor u is on a fresh trail. Accordingly, it first searches for a sink in its neighborhood. If such a sink can be found, the data packet will be forwarded to the sink directly. If not, energy efficient trail based forwarding will be taken. In this process, the holder of the packet will issue a query to check if there exists any neighbor with fresher time stamp (sink-related record) than the current node and starts a timer. A query packet includes the ID of the packet holder and a time stamp as copied from the current node's routing entry. If one reply is received, it will send the data packet to the responding node. If multiple nodes have fresher time stamps than the packet holder, energy efficient next hop selection will be triggered, which takes both trail freshness and residual energy at next hop candidates into consideration. Specifically, sensor *u* will assign a score to each neighbor sending it a reply in the following way:

$$\text{score} = \frac{rest\_energy}{\alpha + \beta(curr\_time - time\_stamp)}$$

where *rest_energy* is the residual energy of the next hop candidate node, *curr_time* is the current time, *time_stamp* is the time stamp of sink record kept at the candidate node (as indicated in the reply message), α and β are network parameters. Usually, α is a natural number to avoid the zero denominator case, β controls the proportion of importance of residual energy and freshness of time stamp. The freshness of time stamp is more important when β is larger. We can see that in the above formula, candidate nodes with more residual energy and fresher time stamp can get higher scores and thus have higher probability to serve as the next hop node. The neighbor node with the highest score will be chosen as the next hop. Then, the packet holder will send the packet to the chosen next hop.

Upon receipt of the packet, the next hop will repeat the above operation. This process keeps going until the packet arrives at a mobile sink. If no reply is received in given time, which means the trail is broken, the two-hop local broadcast mechanism in TBD is used to search for an alternate route for broken point bypassing. When two-hop local broadcast fails to find such an alternate path, node *u* will resort to its backup routing entry by triggering data-driven-based forwarding if it has such a routing entry in its cache. If no such entry is available, energy efficient random walk will be triggered.

(B) *Data-driven-based forwarding*

E-TBD follows the data-driven forwarding in DDRP. The use of this forwarding strategy here is exactly the same to that in TBD. In case DDRP learnt routing table is available and further data-driven-based forwarding is in triggering, the packet holder will choose the next hop in this entry for packet forwarding.

(C) *Energy-efficient random walk routing*

When sensor *u* does not know any route to reach a sink, energy efficient random walk routing will be triggered. For this purpose, a packet holder chooses top 20% neighbor nodes having the most residual energy and give them 80% probability to be chosen and the given the remaining 80% nodes 20% probability to be chosen. For all nodes belonging to the same type, the probabilities for each of them to be chosen are equal. In this way, we ensure certain randomness while giving more opportunity to sensor nodes with more residual energy to serve as packet forwarders and thus protect those neighbor nodes with less residual energy. Upon receipt of the data packet, a sensor node will repeat the above process until the packet reaches next hop with fresher sink record, a mobile sink, a sensor node with DDRP routing table, or timed out and then dropped.

4 Performance Evaluation

This section conducts simulations to evaluate the performance of E-TBD by comparing it with TBD. Both protocols simulated belong to reactive routing protocols and further neither of their implementations assume any location information. The simulator used here was developed using Java in Eclipse environment.

In our simulations, there are multiple mobile sinks and 200 sensor nodes deployed uniformly in a 500×500 m^2 square. The communication range of each node is 60 m. Each sink takes a random direction to move and at a given speed and it will get bounced when reaching the boundary of the sensing area. Data packets are generated at sensor nodes randomly at certain probability.

We assume that the links in the network are symmetric and the length of each packet is 1000 bit. The energy consumption of transceiver circuit is 500 nJ/bit, and the power amplifier is 100 pJ/bit/m^2. Initially, each sensor node has 2 J energy.

In the simulation, three metrics are evaluated: packet delivery ratio, normalized forwarding overhead, and network lifetime. The packet delivery ratio is the ratio of the total number of successfully delivered data packets to the number of data packets generated in the network. The normalized forwarding overhead is the ratio of the total number of packet transmissions over the number of data packets successfully delivered to sink nodes. The network lifetime is the length of time from network starts running to the time when the first sensor is dead due to running out of energy. This metric represents the energy efficiency of a protocol. In our experiments, each point in the figures is the average due to 30 different tests.

Figure 1 compares performance of different protocols in the scenario of one-sink mWSNs and the packet generation rate equals two packets/s. Specifically, Fig. 1(a) shows the delivery ratio performance with varying sink velocity, Fig. 1(b) shows the overhead with varying sink velocity and Fig. 1(c) shows the network lifetime varying sink velocity. Figure 2 shows the results for 3-sink mWSNs with the packet generation rate equals two packets/s. Figure 3 shows the results for 3-sink mWSNs but the packet generation rate equals one packet/s.

From results in Figs. 1, 2 and 3, the data delivery ratio and network overhead by E-TBD is similar to that by TBD. Meanwhile, the network lifetime by E-TBD is much longer than that by TBD. Specifically, as sink(s) move faster in the network, packet delivery ratio by both TBD and E-TBD keeps decreasing and the corresponding protocol overhead keeps increasing. In most cases, the overhead by E-TBD is a little bit higher than that TBD due to the following reasons: (1) E-TBD needs extra messages to exchange energy availability information among neighbor nodes as compared with TBD. (2) when making choice of next hop using trail based forwarding, E-TBD considers both residual energy at next hops and also progress made, while TBD

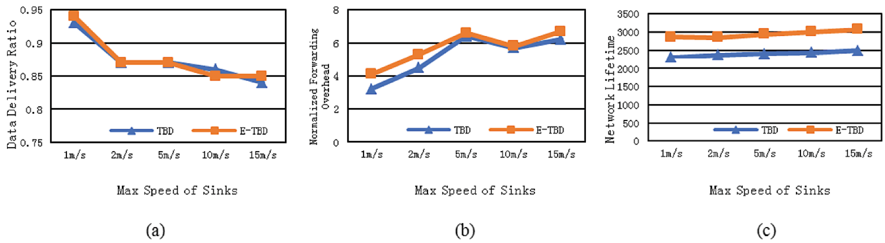

Fig. 1. Performance comparison of different algorithms with varying sink speed. In this test, there is only one sink in the network and packet generation rate is two packets/s.

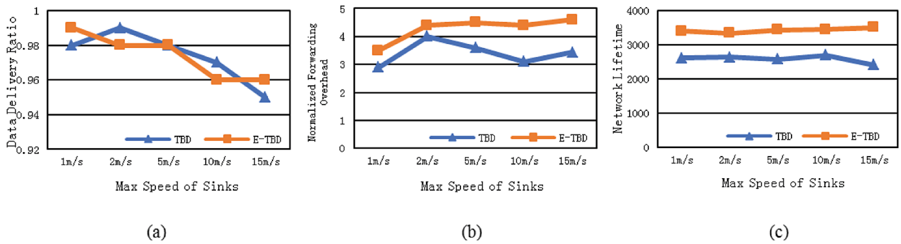

Fig. 2. Performance comparison of different algorithms with varying sink speed. In this test, there are three sinks in the network and packet generation rate is two packets/s.

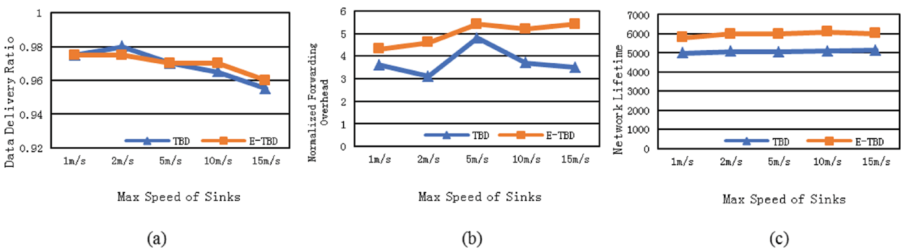

Fig. 3. Performance by of different algorithms with varying sink speed. In this test, there are three sinks and packet generation rate is one packet/s.

considers only progress made for one-hop data forwarding. Obviously, the former choice typically leads to more balancing of energy consumption among nodes but also cause more hops as compared with the latter.

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