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Energy-efficient routing protocols for solving energy hole problem in wireless sensor networks

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ABSTRACT

Recently, researchers introduced energy-efficient dynamic routing protocols for wireless sensor networks to avoid the premature end of network lifetime. This paper addresses the routing hole problem due to energy depletion and the trade-off between the network need for periodic setups to preserve connectivity and power constraints on sensor nodes. The paper solves the problem of the premature end of network lifetime in applications where the base station (BS) is far from the Region Of Interest (ROI). Therefore, we propose two distributed, energy-efficient, and connectivity-aware routing protocols for solving the routing hole problem. These protocols are On-Hole Children Reconnection (OHCR) with local nature and On-Hole Alert (OHA) with global nature. The proposed protocols preserve the connectivity of all single setup phase, single path networks with any topology in an energy efficient manner by avoiding topology reformation overhead. The simulation results proved that the proposed protocols outperform the recent ones in terms of network lifetime, node loss rate, and network overhead. Such that, the two protocols are examined on both Degree Constrained Tree (DCT) and Shortest Path Tree (SPT) to provide about 50% to 75% increase in network lifetime over the recent energy efficient routing protocols; like UCCGRA and NEECP. Additionally, applying OHCR and OHA to any network topology doesn't affect its stability period, since these protocols are triggered by routing hole occurrence.

1. Introduction

The last years have shown a wide range of Wireless Sensor Network (WSN) applications. According to the authors in [1], these applications can be broadly categorized into four main categories: (i) event detection and reporting description applications that are energy conservative by nature, where sensor nodes are in sleep mode for the whole network lifetime and turn to active mode only if an event is detected. (ii) Sink-initiated querying applications that are similar to the previous class; such that, sensor nodes are in sleep mode for the whole network lifetime to be switched to active mode on listening to the sink query. Thus, energy conservation in terms of data transmission is dependent on the frequency of sink queries which is determined by the application need. (iii) Data gathering and periodic measurement applications that involve gathering data from sensor nodes in periodic fashion throughout network lifetime to convey their information to the sink/base station (BS). Thus, it is the most energy consuming class of the previous classes. Finally, (iv) tracking-based applications that combine the characteristics of the previous three classes.

The energy efficient routing protocols designed for data gathering and periodic measurement applications preserve the network lifetime for any other WSN application. Such applications include periodic monitoring, target tracking, and some event-driven and query-based applications that require energy conservation due to the difficulty of human access. Monitoring applications include the following three types. First, ubiquitous monitoring applications [2,3]. Second, healthcare applications [4–7], that include monitoring patient's blood pressure, temperature, heart beat rates and other health indicators remotely to take actions in case of any health problem, environmental surveillance, e.g. monitoring the quality of air [5,6] and detecting oil spill in water [8], and . Third, industrial applications, e.g. pipeline monitoring [9], monitoring the data that are necessary for decision making in Precision Agriculture (PA) for agricultural farm management [10–12], and smart grid system monitoring [13]. Other applications combine more than one class, like the one introduced by the authors in [14] who

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integrated the monitoring forest growth and environmental hazard detection to provide precision forestry.

According to [15], the radio system is the most power consuming part in any wireless communication system, since the transmission power of a wireless radio is proportional to distance squared or higher order in the presence of obstacles. Meanwhile, covering a large Region Of Interest (ROI) influences the energy consideration required for most wireless sensor network applications. Thus, multi-hop routing process for setting up routes is essential instead of direct communication which encourages researchers to design and improve routing protocols to cope with the need for connectivity while considering transmission power consumption, as discussed in [16].

Unfortunately, during the excessive data transmission in data gathering applications, some nodes deplete their energy before other nodes leading to the creation of routing holes. These routing holes disconnect some nodes from the others and thus the coverage of significant part of ROI is lost. The long duration of sensor operation, the many-to-one traffic flow and the nature of the monitored environment, such as forest or battlefield, prevent manual fixing. Thus, various research topics were made to detect energy holes, their causes, and their impact on network performance while providing solutions, as studied in [17–19]. Since data gathering task is not successfully accomplished if sensor nodes in the ROI fail to send their measured data to the BS, this is called a premature end of network lifetime. Accordingly, the authors in [20] and [21] studied the effect of node deployment on the data capacity and showed that about 90% of the energy of the network is left unused while the network lifetime ends prematurely due to energy hole problem that leads to routing holes in the path from the sensor nodes to the BS.

To the best of our knowledge and the findings of [20] and [22] regarding energy hole problem, the previously introduced energy efficient network solutions are based on hop count ignoring the data transmission distance and the recovery solutions are based on one of the following five methods.

- Pre-determined deployment strategy and mobility, as in [21,23–25] and [26,27], respectively, which are infeasible in many monitoring application environments [2,3].
- Network heterogeneity [28], by assuming higher initial energy of some nodes than the others.
- Clustering and dynamic topology formation that has three categories. First, the proactive type that is characterized by periodic data forwarding to the BS, like LEACH [29,30] and PEGASIS [31]. Second, the reactive type that suits the time sensitive applications; such that, if the measured data exceeds a certain threshold or within a predefined range of values, it is transmitted to the BS, like TEEN [32]. Third, the hybrid type, like APTEEN [33]. However, all routing protocols with dynamic topologies introduce topology formation overhead.
- Diffusion-based routing protocols that are characterized by high fault tolerance to cope with topological hole problems [34–36]. However, these protocols are more suitable for event-driven applications than data gathering ones.
- Distributed beamforming transmitters that were studied in [37], where the authors focus on the signal processing related issues including the distributed source coordination for information sharing, timing synchronization, and distributed carrier synchronization . Thus, the energy conservation and connectivity issues are not sufficiently covered.

The premature end of network lifetime is one of the most common issues in single path networks with single network setup phase. This end of network lifetime is a result of losing connection of some nodes with the BS due to energy depletion of the intermediate node. This problem is more probable when the distance between the ROI and the BS is large as studied in [20]. Hence, the nodes responsible for ROI to BS transmission are lost before other nodes. Thus, the ROI is disconnected from the BS although the average network energy is relatively high.

In this paper, we propose two trigger-based, energy-efficient routing protocols that ensure connectivity for periodic data gathering applications. Our proposed protocols On-Hole Children Reconnection (OHCR) and On-Hole Alert (OHA) solve any routing hole problem based on local and global information, respectively. They suit all the topology formation algorithms and network facilities of single path networks with single setup phase. They tackle the premature end of network lifetime in such networks; especially, when the BS is far from the ROI. Moreover, they avoid the continuous dynamic topology formation, unlike other dynamic routing protocols. These protocols dynamically reconnect the disconnected node whenever a routing hole occurs with minimal network setup overhead. The main contributions of our protocols can be summarized in two points. First, they preserve the stability period, as defined in [38], while increasing the network lifetime of the topology formation algorithm. Second, they limit the trade-off between connectivity and network overhead by minimizing the energy consumed in topology reformation while maintaining connectivity.

This paper is organized as follows; in Section 2, the related work is shown with a detailed comparison among the recent energy efficient proactive routing protocols. Problem formulation and basic assumptions are described in Section 3. The two proposed protocols are discussed in Sections 4 and 5. In Section 6, we study our proposed protocols analytically to find the energy cost and derive an ideal estimation of stability period and network lifetime. In Section 7, simulation results of our work are shown in details. Finally, in Section 8, our conclusion with a plan for future work is described.

2. Related work

Energy efficient algorithms for routing data from static sensor nodes in the ROI to a static BS have received considerable attention over the past few years. The most famous routing protocols that lead the improvement in energy efficiency nowadays are LEACH [29,30] and PEGASIS [31]. Although LEACH is a hierarchical, probabilistic, distributed, one-hop protocol that aims at improving the lifetime of WSNs and the most appropriate for maintaining connectivity which is essential for periodic data gathering applications, CHs are not well distributed and a high percent of energy is wasted on periodic cluster formation. This waste of energy during the continuous setup phase is called the protocol overhead in terms of energy consumption and affects the network lifetime severely.

This large overhead has gained the interest of many researchers due to its effect on network stability and lifetime. Accordingly, PEGASIS [31] was introduced to minimize both the setup and data transmission energy consumption using a single chain-based topology. It minimizes the protocol overhead by performing conditional topology change only in case of node loss. However, this node may be at the end of the topology and might not affect other nodes in the topology. It uses the nearest neighbor selection for the chain topology formation which minimizes energy during topology formation and data transmission and distributes the data aggregation task. However, continuous selection of the chain leader that is responsible for ROI to BS transmission is performed to ensure the loss of nodes at random positions. However, simulation results in [39] proved that it adds very high data latency at different network densities and data compression factors. Thus, it is not suitable for large networks or time critical applications.

The proactive routing protocols where sensors report data periodically to the BS are the most suitable for monitoring applica-