Wireless Sensor Networks with Mobile Sink

Subjects: Computer Science, Artificial Intelligence
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With the advances in sensing technologies, sensor networks became the core of several different networks, including the Internet of Things (IoT) and drone networks. This led to the use of sensor networks in many critical applications including military, health care, and commercial applications.

Keywords: path planning ; sensor networks ; energy ; environmental ; mobile sink

1. Introduction

A wireless sensor network (WSN) is a type of network with small, battery-powered sensor nodes that collect data from monitored environments. Such nodes are connected via wireless links to send their collected data to a sink node. However, one of the challenges of WSNs is energy consumption, particularly in large-scale areas with thousands of sensor nodes, since the main supply of energy in sensor nodes is batteries. At the same time, it is hard to recharge the batteries in some monitored areas, especially in hazardous or inaccessible areas. Thus, researchers' primary considerations in this field are the nodes' energy consumption and network lifetime [1][2].

Clustering conserves sensor node energy and improves network longevity. In clustering, the network is divided into groups. Every group has a head or leader. Cluster heads take sensor node data, aggregate it, and transfer it to the sink node directly or via other cluster heads [3]. Cluster heads may lose energy faster than conventional sensor nodes due to the extra load of receiving, aggregating, and transferring data to the sink node. Therefore, cluster heads must be energy-efficient because of transmission and reception operations. The death of these nodes in an area might cause network partitioning and data loss. Thus, proper selection of cluster heads conserves sensor node energy, prolonging network life. Several clustering approaches assign cluster heads based on the average distance to maximize cluster head lifespan in this setting. So, cluster heads are close member nodes. Certainly, if the cluster head dies, it may generate a serious energy imbalance in the network. To increase network lifetime, an energy-balanced clustering strategy is required [4][5]. It is obvious that high-quality, reliable wireless links enabling communication among sensor nodes would be required to successfully deliver the data packet from the member nodes to their cluster heads. However, due to wireless communication's inherent nature in sensor networks, packet losses are quite inevitable. Wireless connections are prone to network disturbances due to some environmental parameters such as interference and fading. This would increase the retransmission possibility of lost packets and thus causes more energy consumption and more delivery delay. Nevertheless, most of the existing clustering techniques attempted to select cluster heads based on energy factors to improve network lifetime. Such approaches lack knowledge related to data transmission interruptions due to lossy links. This eventually affects the network throughput and lifetime. Therefore, the quality of wireless links is another factor that needs to be considered when designing the clustering technique for WSNs [6][7][8][9].

Although the clustering technique contributes to extending the network lifetime, there are still existing issues such as hotspot problems and connectivity. As the most consuming energy in sensor nodes comes from communication, the sensor nodes near to the static sink are at risk of dying more quickly than other nodes because they consume more energy by transmitting accumulative data to the static sink, causing hotspot problems. As a consequence, network lifetime decreases. Therefore, a mobile sink was proposed as one solution to the energy consumption issue in WSNs. The mobile sink may travel near the monitored area events through a planned path, which refers to scheduling the mobile sink's movement and collecting the needed data from sensor nodes. Finding the ideal path for the mobile sink involves collecting data from sensor nodes [10]. Minimizing nodes' distance from the mobile sink certainly conserves energy; it reduces multi-hop communication and addresses hotspot problems, extending network life.

The battery is the mobile sink's primary power source in most applications. Thus, saving energy is crucial to a mobile sink's lifespan. The mobile sink's movement is a key source of energy consumption and costs. Most WSN path planning algorithms try to decrease energy usage to extend the lifetime of the mobile sink. It is important to design an energy-efficient path planning method [11].

The WSNs deployment environment may be heterogeneous. So, the monitored field is divided into small parts called zones, and a certain value is assigned to each zone indicating its priority (importance), namely, its zone priority [12]. The messages coming from sensor nodes located in the high-priority zones are considered urgent data. As urgent data are considered high-priority data, they must be transmitted immediately to the sink node. Suppose such messages occur in an exceptionally high-priority zone that the mobile sink has not visited yet or has visited already. In that case, they should be delivered promptly through a routing technique. Therefore, the mobile sink should move first to the high-priority zones to avoid excessive routing of urgent data. Consequently, urgent data delivery delay and the failure rate can be minimized; the urgent data packets can be delivered directly from the cluster heads that gathered them from their members to the sink node without a routing process. Hence, considering the zone priority in the path planning of the mobile sink can improve the latency and/or throughput of a high-priority data flow. Moreover, it can improve network lifetime by saving the consumed energy during the routing process.

Another challenging issue is that environmental conditions also influence the WSN performance since it is commonly installed in hostile environments, exposing sensor nodes and sink nodes to failure. Thus, the network seldom works. For instance, sensor nodes and sink nodes are more likely to fail at high temperatures and might be entirely burnt out. Moreover, their short-circuit probability would be raised at extremely high humidity [13][14]. Thus, reducing network performance consequences such as temperature and humidity is important. Therefore, the sink node should be prevented from moving through dangerous areas (for example, areas located in a harsh environment). If the mobile sink crosses a risky zone, such as a fire zone, data transmission in the whole network will be cut off due to burned sink node. Consequently, environmental awareness should be considered when designing the mobile sink's path planning algorithm.

Urgent real-time data must be delivered to the mobile sink in real-time (deadline). In this scenario, timely data transmission guarantees that the appropriate actions are made, whereas late data delivery affects the action's efficacy. Therefore, this issue has to be considered in constructing the path planning of the mobile sink [14][15].

Suppose urgent messages such as sudden emergency events occur in sub-areas where the mobile sink has not yet been visited. In that case, such urgent messages should be delivered immediately to the mobile sink through an efficient routing technique. Since the WSN's functioning relies heavily on the battery life of its sensor nodes, developing a routing algorithm that balances energy usage and energy awareness is a big challenge. In addition, as described above, it is important to reduce the effects of environmental parameters (e.g., humidity and temperature) on network efficiency. Therefore, the urgent data packets should be transmitted over paths that would cross a dangerous zone, such as a fire zone, which would inevitably interrupt data delivery once the relay nodes in that zone are burned. Thus, environmental awareness is a crucial factor that needs to be considered when designing a routing algorithm in WSNs. Moreover, since urgent data packets must be delivered reliably and on time, the routing algorithm should prioritize reliable transmission while being suitable for real-time applications [14][15].

For resolving the aforementioned problems, nature-inspired algorithms were developed. Swarm intelligence (SI) is one of such algorithms being explored to deliver effective optimization solutions for a wide variety of WSN situations because of their flexibility and adaptability in solving many complex problems. Almost all swarm intelligence optimization approaches are inspired by ant colonies, bees, and animal swarms. The ant colony optimization (ACO) approach resembles social ant colonies. In particular, ants use pheromones as a chemical messenger, and the pheromone concentration is also used to indicate solution quality in ACO to find the ideal solution. Therefore, the problem's solution is usually related to pheromone concentration [9][16][17]. The work in this research consists of three phases. The first phase is proposing an efficient means of mobile sink path planning as many researchers based their research on problems related to the path planning of the mobile sink. Most of them also tried to determine the shortest path with the least cost and time [18][19][20][21][22][23][24] without considering the environmental effect, which may be affected by path changes. Path planning under difficult situations is uncertain. Therefore, this research uses environmental awareness to reduce mobile sink's environmental effect. Secondly, the consequence of the excessive routing of urgent data would negatively influence the latency and/or throughput of a high-priority data flow. Hence, the zone priority is considered when deciding on a new mobile sink location. In addition, delivery delay and distance are also considered. In the second phase, a cluster head is chosen. The proposed clustering strategy chooses cluster heads from normal sensor nodes based on energy efficiency and network reliability to improve network lifetime and throughput. It considers sensor node residual energy, wireless link quality, and intra-cluster distance.

The third step is the routing algorithm. Up to the knowledge, numerous research publications have examined WSN routing problems. Most suggested solutions aimed at increasing data transmission reliability and energy efficiency [9][25][26]. Such studies do not address the environmental effect in routing protocol design. Therefore, they cannot adapt quickly to environmental disturbances like rainstorms and wildfires. To the best of the knowledge up to the time of writing this research, only two routing protocols [13][14] considered energy and environment awareness when seeking to increase routing reliability and energy efficiency under hostile situations. The problem with these algorithms is that they cannot be used in real time. So, this research suggests a routing algorithm which tries to reduce the adverse environmental effects on data delivery and is also suitable for real-time applications. It also looks at the link quality so as not to send data packets down paths that are not reliable. Moreover, a novel function interrelates residual energy, and sensor node load is advocated to balance energy utilization.

The path planning, cluster head selection, and routing problems are formulated in the form of 0/1 integer programming for other researchers to understand and reuse. Then, swarm intelligence is introduced as a heuristic solution for the three problems.

2. Wireless Sensor Networks with Mobile Sink

Researchers have proposed numerous ways to prolong the network lifetime. Mobile sinks are one of the most effective solutions for reducing WSN energy usage and improving network lifetime. Due to its relevance in real-world applications, academics and researchers are interested in mobile sink path planning. WSNs are the foundation of IoT applications; mobile sink path planning is considered one of the key factors underpinning their efficacy.

Recent research divides the sink mobility problem into optimum mobile sink paths with and without clustering. Since the research most related to the proposal is the optimal mobile sink path planning with clustering, this section starts with the description of the algorithms that are mostly related to the proposed solution presented in [18][19][20][21][22][23][24]. Then, it discusses their differences from researcher's proposal as well. Finally, as the research presented in [18][19][20][21][22][23][24] does not address the cluster-based routing problem for inter-cluster communication, which is one of this researcg's main objectives, this section discusses the proposed solution compared to the related research presented in [27][28].

An energy-efficient route planning strategy for wireless sensor networks (WSNs) with several mobile sinks is proposed by the authors in [18]. This method is based on a stable election algorithm (SEA) and clustering algorithms for homogeneous and heterogeneous sensor networks. This work aimed to increase network life and connection. The stable election algorithm reduces message flow between sensor nodes and prevents redundant cluster head rotation. Cluster initiation, head rotation, and data collecting make up the SEA. After sensor node deployment, cluster initiation starts. The sensor node with the most neighbors in a homogeneous network is the initial cluster head. The initial cluster head depends on surrounding nodes and node energy in a heterogeneous network. When residual energy drops below a threshold, cluster heads rotate. The node with the greatest rotation index will be the cluster leader. The sink node receives data from nearby cluster heads. Mobile sink path planning examined sojourn locations using the minimum weighted vertex cover problem (MWVCP). The optimal sink path should visit all sojourn spots; however, an MOEA is used to decrease cost, distance, and time.

The authors of [19] present an evolutionary game-based mobile sink trajectory design algorithm (EGTDA). The model of the evolutionary game considered each cluster's average residual and inter-cluster energy consumption. The mobile sink travels to a cluster with the highest residual energy and the shortest distance to surrounding clusters. This model proposes a clustering algorithm that compares each node to its neighbors to find the cluster head. When two nodes have the same amount of remaining energy, a smaller node ID is selected. This is done to ensure that each cluster has only one cluster head.

KH-TSP optimizes mobile sink paths in large-scale wireless sensor networks [20]. Iterative filtering is used to aggregate the collected data into cluster heads. K-mean clustering is utilized to group randomly placed sensor nodes. It utilizes residual energy and node proximity to construct second-level clusters. TSP used these clusters to build the optimal path sequence. The sequences number is merged to produce a population for the krill optimization method, where the average delay in each sequence is evaluated. The population was designed to reduce delay. The KH-TSP facilitates large-scale WSN data collection, conserves energy, and extends the network's lifetime.

The clustering-based movable sink route approach was suggested by the authors of [21]. To minimize the sink distance between sensor nodes, they used fuzzy logic. They divided the field into 16 equal zones and made an attempt to calculate the sensor residual energy that should be taken into account. Fuzzy logic and mobile sink nodes increased network longevity, particularly in large-scale networks.

For efficient data collection, the authors of [22] investigated clustering algorithms using mobile sink nodes. They use a modified LEACH approach as the foundation for their clustering. ACO also determines the most direct route for a mobile sink to go to cluster heads and then return to its starting location. Reduced data loss and increased network longevity were the goals.

A clustered data gathering technique for mobile sink nodes is presented by the authors of [23]. In this algorithm, the entire network is split into grids or cells with equal size. To balance the energies of the sensor nodes, the cluster head is chosen depending on the remaining node energy. Moreover, the chosen cluster head should be close to the grid centroid. To maximize network data gathering and establish the shortest path to each mobile sink, an artificial bee colony technique is used.

Reference [24] suggests a WSN routing method based on ACO with mobile sinks (EARP). The WSN multi-sink cluster paradigm is offered by this energy-saving technology. The cluster head, where ACO is used to calculate the optimum route for the mobile sink, is decided by residual energy and distance from sensor nodes. The authors suggested a trustworthy technique for effective energy. However, after examining earlier studies [18][19][20][21][22][23][24], it is clear that they have the following limitations:

- They ignore environmental consequences. Environmental factors may cause sensor and sink nodes to fail, causing the network to malfunction. Neglecting this challenge might make them unable to adapt to environmental changes like wildfires and rainstorms, impairing network performance. Few research publications have explored the external environment's detrimental influence on data fusion and delivery [13][14]. Unfortunately, up to the knowledge, no research paper has studied the data collection problem of WSNs with mobile sinks under harsh environmental conditions;

- They ignored zone priority. Messages coming from sensor nodes located in high-priority zones should be transmitted immediately to the sink node. Hence, ignoring zone priority could increase urgent data delivery delay and failure rate, which negatively affects the latency and/or throughput of a high-priority data flow;

- They overlook the dependability of data transmission. WSNs depend on reliable data transfer. Ignoring such concerns might increase packet loss, waste energy, and delay packet retransmission. This clearly impacts network efficiency;

- They miss real-time data transmission. Real-time delivery of data is difficult in WSNs. Transmission of crucial real-time data within a predetermined deadline enables prompt action, whereas late delivery reduces the efficacy of the action done. Ignoring this problem might increase missed deadlines and packet drops. **Table 1** provides an overall comparison of the algorithms mentioned earlier [18][19][20][21][22][23][24] and the proposed ones.

Table 1. A comparative summary of the algorithms mentioned above and the proposed ones.

Paper ID	Path Planning Parameters							Cluster Head Selection Parameters		
	Moving Cost	Travelling Delay	Traveling Distance	Cluster Head Energy	Areas (Zones) Priority	Environmental Impact	Real Time Delivery	Residual Energy	Distance	Reliability
[18]	√	√	√	×	×	×	×	√	×	×
[19]	×	×	√	√	×	×	×	√	×	×
[20]	×	√	×	×	×	×	×	√	√	×
[21]	×	×	×	√	×	×	×	√	√	×
[22]	×	×	√	×	×	×	×	√	×	×
[23]	×	×	√	×	×	×	×	√	√	×
[24]	×	×	√	×	×	×	×	√	√	×
Proposed Solution	√	√	√	×	√	√	√	√	√	√

With regard to the cluster-based routing problem for inter-cluster communication, many academics have investigated this problem, where each cluster head assigns a relay node to forward collected data to the sink node [27][28][29]. In the related protocols [27][28], each cluster head picks its next-hop relay node using a cost function to reduce and balance sensor node energy consumption. Cost function incorporates energy efficiency, residual energy, and distance.

The prior research of similar algorithms demonstrates that they have limitations since they ignore critical issues. The first concern is the environmental effect; disregarding it will instantly cut off WSN's data delivery. Second, they do not account for lossy links caused by fading and interference; ignoring such a problem might increase data loss, retransmission delay, and energy waste. Finally, they cannot achieve real-time communications; therefore, they cannot send data packets before the deadline. As has been said, timely data supply ensures relevant actions are made, whereas late data delivery reduces the efficacy of such activities. **Table 2** provides an overall comparison of the two algorithms mentioned earlier [27] [28] and the proposed one.

Table 2. A comparative summary of the two algorithms mentioned earlier [27][28] and the proposed one.

Paper ID	Cluster-Based Routing Parameters					
	Distance	Residual Energy	Traffic Load	Reliability	Environmental Impact	Real Time Delivery
[27]	√	√	×	×	×	×
[28]	√	√	×	×	×	×
Proposed Solution	√	√	√	√	√	√

Motivated by the above discussion, the following points are advanced in this research:

- Researchers present a unique data collecting path planning technique that considers environmental effect parameters to reduce mobile sink environmental impact. It achieves this by calculating each node's environmental effect. Then, it avoids cluster heads in dangerous zones by choosing cluster heads with a higher final environmental impact measure to participate in path planning. Moreover, the zone priority is considered to avoid the excessive routing of urgent data, which would negatively influence the latency and/or throughput of a high-priority data flow. A new zone priority metric function is proposed to integrate the zone priority into the path planning process. The movement cost is thought to reduce the amount of wasted energy during movement, which will make the mobile sink last longer. The movement delay is also considered for real-time urgent data transmission and decreases the chance of buffer overflow of sensor nodes owing to its restricted buffer capacity;

- Secondly, researchers propose an energy-efficient clustering technique considering the average intra-cluster distance, residual energy, and reliability of intra-cluster data transmission. In the cluster hierarchy, aggregating the data by each cluster head from its members causes imbalanced energy loss. A novel energy weight function is presented to pick the most energy-efficient node as a cluster head and avoid selecting low-residual-energy nodes. To achieve reliable intra-cluster data transmission, a new link quality metric function is suggested to express the quality of links between each candidate cluster head and its member nodes. Researchers assess the average intra-cluster distance to improve end-to-end latency, as with many previous clustering approaches;

- Third, researchers offer a real-time, reliable, energy-efficient, and environment-aware routing approach. The suggested routing strategy minimizes the external environment's impact on data transmission. Link quality is also considered to prevent data forwarding over unstable paths; a novel function that combines sensor node residual energy and traffic load balances energy usage is proposed. It provides real-time WSN transmission. Only qualified neighbors who can deliver urgent data on time participate in the routing procedure. Moreover, it calculates the relaying delay for each eligible candidate neighbor to reduce route latency. The suggested routing approach uses more realistic parameters than prior systems;

- Lastly, these problems involve 0/1 integer linear programming. Then, swarm intelligence is proposed for optimization problems.

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