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Smooth path construction and adjustment for multiple mobile sinks in wireless sensor networks[☆,☆☆]

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ABSTRACT

Wireless multimedia sensor networks can provide a much clearer picture of the sensed area and thus significantly improve many applications. However, the increased amount of data will lead to issues with energy consumption and network lifetimes if we use the traditional network-based data collection where packets are forwarded hop by hop to the base. To mitigate these problems, researchers have been investigating mobile sinks traveling through the network and collecting the generated data. Using mobile sinks significantly increases the delivery rate while also reducing energy usage, but this increases the collection delay because of the physical speed of mobile sinks. In this paper, to reduce the physical collection delay while maintaining the other performance improvements (e.g., delivery rate, energy usage), we focus on how to use faster mobile sinks. Such mobile sinks are often motion-constrained and require smooth paths which can be followed with these constraints. Accordingly, we first developed a basic smooth path construction algorithm based on the TSP. We then extended it with path adjustments based on the required contact time at each node. Finally, we allowed for multiple mobile sinks which allowed us to further reduce the average delay per packet over the previous algorithms. Through extensive simulations, we found our algorithm allows for faster data collection over the current solutions, which can only accommodate flexible but slower mobile sinks, while maintaining the increased delivery rate and decreased energy usage.

1. Introduction

Wireless sensor networks (WSNs) have received significant attention due to their potential use in several different real-world applications [1–3]. To increase the capabilities of such applications, the underlying WSNs are being enhanced with *multimedia sensors* that can capture and process both audio and video data. This new form of WSNs is known as wireless multimedia sensor networks (WMSNs) [4]. WMSNs are expected to have huge impacts on various applications such as multimedia surveillance sensor networks as they can provide a much clearer and explicit image of what is happening in the sensed area.

This increase in ability also comes with many drawbacks and issues which need to be addressed. The major drawback for WMSNs is the immense increase in the amount of data that needs to be collected. Trying to collect such an immense amount of data using traditional multi-hop forwarding will cause excessive use of the underlying energy-scarce nodes and inherently unreliable wireless links, leading to diminished network lifetimes and low data collection rates, respectively. These would be especially troublesome in large-scale applications of WMSNs such as forest monitoring, wild-life animal tracking, or border monitoring.

To provide a longer lifetime while increasing multi-sensory data collection rates in WSNs, the research community has exploited the use of mobile sinks [5–7]. A mobile sink could be a robot that moves through the network to collect data directly (or indirectly within a few hops) from each node and then takes the collected data back to the base station. This is in contrast to traditional network forwarding (multi-hop routing), which percolates the data through the network towards the sink. Since the mobile sink approach eliminates multi-hop routing and network forwarding, it is expected to significantly improve the network lifetime and the data collection rate as we further justify the advantages of using mobile sinks instead of network forwarding in Section 3. Accordingly, researchers have been extensively investigating various aspects of mobile sinks, as we discuss in Section 2. However, there are still several challenging issues that need to be further investigated in the context of various applications of WMSNs.

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One important implied assumption behind the data collection mechanisms using mobile sinks is that the collected data must be delay-tolerant as the collection delay is bounded by the physical distances and the speed of the mobile sinks. Clearly, this whole approach would not be appropriate when we need to collect real-time data, for which new approaches need to be developed as we are currently investigating in a related work [8]. For monitoring applications that are able to perform their expected functionalities as long as the data transmission is done within hours or minutes, then we can consider mobile sinks. In such applications, to make better analysis and decisions, we need to get almost all of the data from sensor nodes to the base station (i.e., provide a high delivery rate) while minimizing the collection delay as much as possible.

In this paper, we investigate how to use mobile-sink-based data collection in the context of large-scale applications such as forest monitoring and particularly border monitoring, where a country uses WMSNs to monitor its border to stop terrorists from entering and wreaking havoc on its nation. Consider, for example, a WMSN that can be deployed along a border to be monitored for illegal activity or environmental changes. Because of the long distances, it is necessary to use a *faster* mobile sink to reduce the physical collection delay. In this regard, an unmanned aerial vehicle (UAV) would be an ideal mobile sink, as it can quickly visit the nodes in the network and return to the base station with the collected data.

To start with, we need to first provide the UAV with a *minimum length tour* that passes through the locations of the gateway nodes that have data to send. Obviously, this is a variation of the traveling salesman problem (TSP), where each city is a gateway node and the base station is the starting and ending city. As we discuss in the next section, significant work has been done on the TSP. However, since the existing algorithms are not concerned about the motion restrictions of the underlying vehicles, they generate paths/tours with sharp turns that cannot be traveled by UAVs. To be able to use a UAV as a mobile sink, we need to find not only a minimum length tour, but also a *smooth* tour that can be traveled by a vehicle with turning constraints.

In response to this, we propose a smooth path construction (SPC) algorithm. In essence, our algorithm starts with a base TSP tour, which is found by using an existing algorithm, and transforms this tour into a smooth one that can satisfy the turning constraints imposed by a given UAV. When following this smooth path, the mobile sink will have a certain amount of contact time with each gateway node. However, this limited time may not be enough to collect all of the data at some gateway nodes. In such cases, we will need to adjust the path to increase the contact time. If more contact time is needed, we can resend the mobile sink on the same path, but this would significantly increase the physical collection delay for the gateway nodes with a lot of data. Instead, we propose to add multiple loops around the gateways that have more data to transmit. If less contact time is enough, then we can reduce the length of the arc while passing through the gateway nodes that have less data. Accordingly, we extended our SPC algorithm with path adjustments so that the mobile sink will have enough contact time to collect all of the data at each gateway node in one trip while minimizing the total distance and maximum travel time.

We are able to minimize the maximum delay per packet through the provided smooth and adjusted paths. However, there is a certain limit to how much we can reduce the maximum delay per packet using a single mobile sink. We can reduce the maximum delay per packet further by adding more mobile sinks. This will obviously make the problem of path planning and coordination more difficult while making data collection more efficient and faster. The problem of using multiple sinks can be modeled as the vehicle routing problem (VRP) [9], where each mobile sink is modeled as an uncapacitated vehicle and each gateway node is a demand point.

The VRP has been very well studied and has been proven to be NP-complete [9]. Accordingly, researchers have proposed several heuristics to solve it [10]. The problem with many of these heuristics, however, is that they attempt to minimize the distance traveled by all of the vehicles, but when there are multiple vehicles, minimizing the distance does not guarantee minimizing the maximum delay per packet as aimed at in our paper. Instead, we propose a new heuristic that divides the gateway nodes into as many clusters as the number of mobile sinks. It then uses our SPC for each of these clusters.

For performance evaluations, we used extensive simulations. We compared our SPC algorithm to that in [11] which used a more traditional version of Dubins curves. Our SPC algorithm improves on the distance traveled by a mobile sink, particularly in the settings where more turns are required. We also show that the SPC with adjustment algorithm gave us the ability to improve the distance traveled when there is a small amount of data at a gateway node while also improving both the delivery rate and maximum delay per packet in all cases over our original SPC algorithm. Our experiments showed that in the case of using multiple mobile sinks, our cluster-based heuristic improves the delay per packet by nearly 1.5 times when compared to the performance of solving the VRP using the algorithm in [10].

In summary, our main contributions are as follows:

1. We propose a smooth path construction algorithm (SPC) algorithm that determines the path to be followed by a UAV for data collection.
2. We extend SPC with path adjustments to collect all the data at each gateway node in one tour.
3. We propose a clustering-based algorithm to coordinate multiple sinks to collect data using the SPC and its extension.
4. We use extensive simulations to verify and show the efficiency of our algorithms.

The rest of this paper is organized as follows. In Section 2 we present the related work. We then present the problem formulation in Section 3. We describe our proposed smooth path construction (SPC) algorithm in Section 4. Section 5 contains a description of our adjusted algorithm. We expand the problem to multiple mobile sinks in Section 6. In Section 7 we present our simulation setup and the results. Finally, we conclude this paper and discuss some possible future work in Section 8.

2. Related work

2.1. Mobile sinks

Using mobile sinks (or data mules) to assist in data collection has become a popular avenue for research in WSNs. Mobile elements can increase connectivity and reliability, reduce costs, and decrease energy consumption at individual nodes [7]. However, these benefits are gained at the cost of increased latency for the data gathered by the mule. To get the maximum benefit with the minimum cost, it is essential that the work done by data mules be scheduled in an efficient manner [12]. In [12] the data mule scheduling (DMS) problem is broken into three parts: path selection, speed control, and job scheduling. In [13] the authors study only the speed control part and briefly explain the job scheduling aspect, presenting feasible solutions. The path selection problem is related to the well-studied vehicle routing problem and traveling salesman problem. However, this field is still open, specifically when the vehicles have motion restrictions.

Approaches to using data mules use different mobility models to describe the type of motion in the system. Some systems opportunistically take advantage of mules with random mobility, i.e., motion not controlled by the operation of the network. Others propose a periodic mobility model akin to a city bus route, where the mule moves regularly through the network, but is not necessarily controlled by the network and its route cannot be changed. The most useful, and most