Monitoring Quality Optimization in Wireless Sensor Networks with a Mobile Sink

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ABSTRACT

The exploitation of sink mobility has been proven to improve various network performance significantly, including network lifetime, data delivery latency, network connectivity, and so on. In this paper we consider a novel network model consisting of sensors, gateways, and a mobile sink, which can be applied to many realistic applications such as city traffic monitoring, patients monitoring, and forest fire surveillance. We assume that there is a roadmap in the monitoring region for the mobile sink to access, and gateways are located on roads. The mobile sink moves at a constant speed along a closed tour of roads to collect data from gateways. The travelling distance of the mobile sink per tour is bounded by a given value. Due to the limited communication time between the sink and each gateway, sometimes it is not possible for the mobile sink to collect the data generated from all sensors, consequently causing monitoring quality loss. In this paper, we study the problem by formulating it to find a closed tour for the mobile sink, such that the monitoring quality loss is minimized, subject to the tour length constraint. Since the problem is NP-hard, we propose a heuristic for it. Also, we design an energy-efficient routing protocol for data collection that balances the energy consumption among sensors. We finally conduct extensive experiments by simulation to evaluate the performance of the proposed schemes. The experiment results show the effectiveness of the proposed heuristic to optimize the network performance.

1. INTRODUCTION

Mobile sinks (MSs) have been exploited in wireless sensor networks (WSNs) to improve the network performance. The use of MSs effectively shifts the burden of data transmission from individual sensors to themselves, thus balancing the energy consumption among sensors and thereby prolonging the network lifetime [13]. Also, they enable more reliable transmission between data sources and destinations [17], improve the network throughput [18], and reduce the data delivery latency effectively [8].

In reality, however, there are several practical constraints imposed on MSs. First, mobile sinks are usually devices installed on robots, shuttles, or airplanes, which are powered by petrol or electricity and supposed to be recharged/refueled over time. Once they start moving in the network, the maximum travelling distance per tour is subject to their power sources. Thus, the length of each MS is constrained. Second, vehicles with MSs cannot travel anywhere in a monitoring area without restriction [1]. Obstacles such as ponds, bushes, buildings, and rocks should be avoided. Moreover, vehicles like city commuters can only stop at stations instead of any spot on the road. Fig. 1 is an example of a WSN deployed in a city while the mobile sink is carried on a bus starting from S. The roadmap for the bus is comprised of all roads in Fig. 1. Before the bus runs out of petrol, it is supposed to return to S. Third, the speed of a MS is usually bounded by multiple factors, such as, traffic conditions, engine limitations, and speed restrictions on highways or in suburbs. Other constraints imposed a MS include the maximum distance between its two consecutive sojourn locations, the minimum time for the MS to stay at a sojourn location [5], and the candidate sojourn locations for the MS [3].

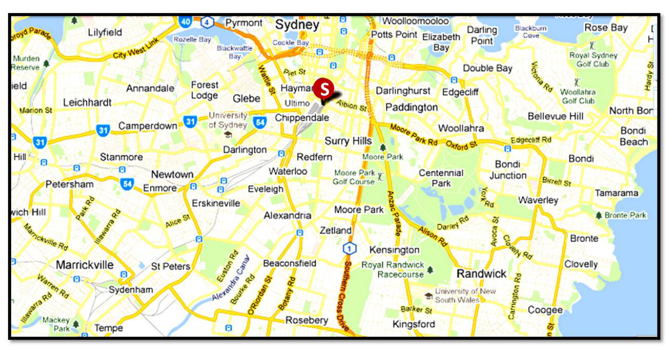

Figure 1: A roadmap for the mobile sink

In this paper, we consider a MS moving in a given roadmap M for data collection while it must return to the depot for data uploading and fuel refilling after each tour, and the tour length is bounded by L. There are some applications falling into this category. One example is a sensor network deployed in a city where the shuttle equipped with the sink

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has a fixed route and returns to the depot at the end of each tour. These two constraints restrict the movement of MSs.

There are some *gateways* located on each road in the roadmap, playing the roles of data relay, storing data generated from sensors temporally and transmitting data directly to the MS later. Gateways are assumed to be rechargeable and have enough buffer capacities to store data before transmitting to the MS. Data collection from a gateway only happens when the MS moves within the transmission range of the gateway. This mode of data transmission has several advantages. First, the MS does not have to visit every sensor deployed in the network, reducing the data delivery latency, especially for large scale networks. Second, having the MS visit partial nodes balances the energy consumption among sensors and the trade-off between energy conservation and delivery delay can be achieved. Third, collecting data from gateways, rather than a large number of sensors, decreases the overhead of constructing routing structures.

In this paper, we take into account the time spent on data uploading from gateways to the MS. Sometimes the MS is not able to collect data generated from all sensors. For example, if the monitoring region is large and the length constraint is relatively small, the MS can only traverse a portion of all roads in the map and visit some of the gateways. In that case, monitoring quality loss is unavoidable. Data generated from some sensors, referred to as *active nodes*, can be collected while those from others, referred to as *inactive nodes*, have to be discarded. We assume sensors densely deployed in the network, thus, the sensing data is highly spatially and temporally correlated, especially among neighboring sensors [19, 6]. The sensing data of active nodes can be used to estimate that of inactive nodes and the estimation error is used to measure the monitoring quality loss. Choosing different roads as a tour for the MS, the monitoring quality loss varies. Also, having the set of active nodes and their corresponding gateways, an appropriate routing structure is needed to enable the successful and efficient data collection. The objective of this paper is to *find a closed tour on the given roadmap for the MS starting from the depot each tour and design a routing protocol, such that the MS is able to efficiently collect data with minimized monitoring quality loss, and return to the depot at the end of each tour subject to the length constraint*.

Our main contributions are as follows. We first define the monitoring quality and formulate the quality optimization problem as a joint optimization problem. Due to its NP-hardness, we then propose a strategy to find a closed tour for the MS meeting the length constraint. We also devise an energy-efficient routing protocol for network lifetime prolongation. We finally conduct extensive experiments to demonstrate the effectiveness of the proposed algorithms.

The rest of the paper is organized as follows. Section 2 discusses the related work. Section 3 proposes the problem formulation. Section 4 and Section 5 present a novel two-stage heuristic algorithm consisting of the length-constrained tour finding and the energy-efficient data routing. Section 6 evaluates the performance of the proposed algorithm through simulations. Section 7 concludes the paper.

2. RELATED WORK

Controlled sink mobility has been extensively studied to mitigate uneven energy consumption among sensors in WSNs [1, 2, 3, 4, 13]. The basic idea is to shift the relay workload from the individual sensors to the mobile sink(s). The mobile sink(s) can either (i) visit every deployed sensor and gathers its generated data via one-hop transmission [4]; (ii) visit some nodes, referred to as sojourn locations in [13], and collect data generated from all sensors at each sojourn location; or (iii) visit gateways, referred to as *rendezvous points* in [2], and collect data generated from partial sensors at each gateway. The first mode of data collection is the most energy-efficient but it may cause long data delivery latency. In the second mode, the data delivery delay is minimized at the cost of unbalance in energy consumption among sensors. The traditional *sink neighborhood problem* [17] is not solved and still compromises the network performance. The third mode is the hybrid of the previous two. The trade-off between the data latency and the energy consumption can be achieved. Our paper falls into this category.

Previous works have discussed sink mobility based on a hybrid mode of data collection. Xing *et al.* [2] aimed to find a set of rendezvous points (RPs) with the objective to minimize the energy consumption on data collection. The optimal locations of RPs are identified subject to the constraint on data delivery latency. Rao *et al.* [7] considered the k multi-hop data collection problem with a mobile sink, where k is a configurable parameter. The desirable balance between energy efficiency and data delivery delay can be achieved by varying k. In [9, 10], data generated from remote sensors are sent to the ones more closed to the moving path of the mobile sink and the sink will pick up the data when it passes by.

In some practical applications, however, the mobility of the sink is constrained. For example, in [11], mobile sinks can only move in a given roadmap and should start from and return to the depot after finishing each tour. Assuming the mobile sinks can visit all walking paths in the roadmap, the problem in [11] is to minimize the maximum path length of mobile sinks, which is then reduced to min-max k-Chinese postman problem (MM k-CPP). Unlike their work, besides the roadmap constraint on the mobile sink, we assume the length of each tour is bounded and consider the monitoring quality optimization problem. In [1], the mobile sink is supposed to move along a fixed trajectory and visit the fixed set of gateways. In this work, the moving path for the mobile sink is to be determined from the given roadmap subject to the tour length constraint such that the monitoring quality is maximized.

3. PRELIMINARIES

Consider a wireless sensor network $G = (V \cup GW, E)$ where V is the set of low-cost sensors, GW is the set of powerful (or solar-powered), large-storage gateways, and E is the set of links connecting sensors and gateways. $n = |V|$, $n_g = |GW|$, and $m = |E|$. There is a given roadmap $M = (V_r, E_r)$ in the monitoring region for the MS, where E_r is the set of roads in the roadmap and V_r is the set of road intersections. $n_r = |V_r|$ and $m_r = |E_r|$. $V_r = \{p_1, p_2, \ldots, p_{n_r}\}$. It indicates that the MS can only move along the roads in the map. Gateways are deployed on the roads and communicate with the MS when the MS moves within the transmission ranges of gateways. Each gateway in GW and each sensor in V equipped with an omni-directional antenna has a fixed, identical transmission range r. Assume the locations of GW and V are stationary and known a *priori*. There is a link between two sensors, or a sensor and a gateway, if they are within the transmission range of each other. Assume that each sensor in V has identical data generation rate r_g.

Two constraints are imposed on the MS: the MS should start from and return to the depot p_0; its total travelling distance per tour should be no longer than L. Also, the MS moves at a constant speed v.

3.1 Monitoring quality loss

Let $GW = \{g_1, g_2, \ldots, g_{n_g}\}$ be the set of gateways. The MS collects data from g_k when it moves within the intersection of the road and the transmission range of g_k. Denote by I_k the length of the intersection for gateway g_k, $1 \le k \le n_g$. Note that the longest I_k is two times of the gateway transmission radius r, i.e., $I_k \le 2 \cdot r$, for $1 \le k \le n_g$. Assuming that there is no data aggregation on gateways or sensors, the maximum amount of data that can be collected by the sink from g_k per tour is

$$data(g_k) = \frac{I_k}{v} \cdot r_k \le \frac{2 \cdot r \cdot r_k}{v}, \ 1 \le k \le n_g, \qquad (1)$$

where r_k is the data transmission rate of gateway g_k. Thus, the upper bound on the number of active nodes for g_k is the number of sensors that can transmit their data to g_k, while all their data can be collected by the MS in the next tour,

$$c(g_k) = \lfloor \frac{data(g_k)}{\frac{L}{v} \cdot r_g} \rfloor \le \lfloor \frac{2 \cdot r \cdot r_k}{L \cdot r_g} \rfloor, \ 1 \le k \le n_g, \qquad (2)$$

$c(g_k)$ is referred to as the *quota* of g_k.

The monitoring quality loss will occur when not all sensing data is collected by the MS in a tour. Assuming a closed tour P subject to L is found, the set of gateways deployed on the roads in P is $GW' \subset GW$. Let D_a be the set of nodes, whose generated data can be collected by the MS, referred to as *active nodes*, and $n_a = |D_a| \le \sum_{g_k \in GW'} c(g_k)$.

The monitoring quality loss is defined as the error caused by data estimation of uncollected data, using the collected ones. Assume x_{tj} is the actual reading of sensor v_j at time t, and $\widehat{x}_{tj}$ is an estimate of x_{tj}. We denote by $QL(P, D_a, V)$ the quality loss with D_a as the set of active nodes:

$$QL(P, D_a, V) = \frac{\sum_{v_j \in V - D_a} \sum_{t=1}^{L(P)/v} (x_{tj} - \widehat{x}_{tj})^2}{n \cdot L(P)/v}, \qquad (3)$$

where $L(P)$ is the length of a tour P and $L(P) \le L$.

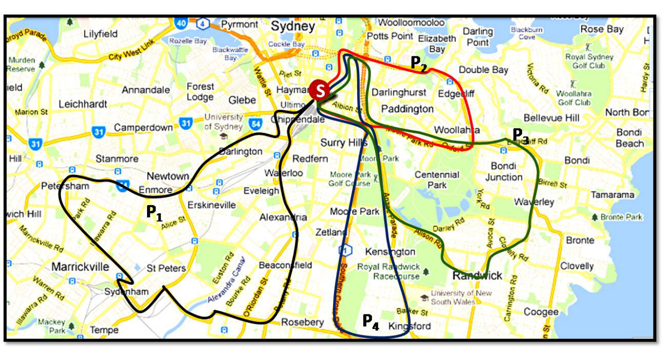


Figure 2: Tour options for the mobile sink

In Fig. 2, for instance, there are four candidate closed tours P_1, P_2, P_3, P_4. Assuming the length of P_1 exceeds L, it should be eliminated. If travelling along P_3 results in the minimum quality loss among the three tours, P_3 should be selected as the tour for the MS.

The *distance-constrained monitoring quality optimization problem* in a sensor network $G = (V \cup GW, E)$ with a mobile sink starting from depot p_0 and moving in a given roadmap $M = (V_r, E_r)$ at a constant speed v is to jointly identify active nodes, find a closed tour P subject to the length constraint L, and design an energy-efficient routing protocol for data collection, such that the mobile sink is able to efficiently collect data from active nodes with the minimum monitoring quality loss and return to p_0 at the end of each tour.

The problem in [1] is a special case of the problem concerned in our paper without the tour length constraint, where there is only one road in the roadmap and the fixed trajectory for the MS is the round trip on this road. Since the problem of data quality maximization with the MS moving along a fixed trajectory has been proven to be NP-hard [1], the problem concerned in this work is NP-hard, too.

4. FINDING A LENGTH-CONSTRAINED TOUR

Due to the NP-hardness of the problem, we propose a two-stage heuristic, which consists of finding the length-constrained tour for the MS and devising a routing protocol for data collection (see Section 5). The tour finding stage is comprised of the following three steps.

4.1 Identifying the set of candidate active nodes

As mentioned in Section 1, we need to explore the spatial correlation among data generated from all sensors before we can determine the set of active nodes.

We Assume that L is large enough so that the MS can traverse all roads in E_r. We aim to identify the set of active nodes $\mathcal{CS}$ to minimize the monitoring quality loss. To do so, we collect data generated from all sensors within a *training period* P_t. The problem is then reduced to the *quota-constrained data quality maximization problem* in [1] and the method in [1] can be adopted to determine $\mathcal{CS}$.

Nodes in $\mathcal{CS}$ are referred to as *candidate active nodes* because the constraint L has not been considered at this stage, and not all data generated from sensors in $\mathcal{CS}$ is guaranteed to be collected by the MS. With the set $\mathcal{CS}$, the monitoring quality is the best case. If $L < \sum_{e \in E_r} dist(e)$ is taken into account, where $dist(e)$ is the Euclidean distance between two endpoints of e, only nodes in a subset of $\mathcal{CS}$ are able to transmit their data to the MS, compromising the monitoring quality.

The following steps are based on this set of candidate active nodes. After the tour is found, the MS will move along it in the following *operation phase* P_o. Then the tour is to be re-identified and the training and operation phases are repeated.

4.2 Allocating candidate active nodes to gateways

Having identified the set of candidate active nodes, we first allocate them to gateways, subject to the gateway quotas. That is, partition $\mathcal{CS}$ into n_g disjoint subsets $D_1, D_2, \ldots, D_{n_g}$ for gateways subject to $c(g_k)$, $1 \le k \le n_g$, using the method in [1]. These subsets satisfy: (i) $\bigcup_{k=1}^{n_g} D_k = \mathcal{CS}$, $D_k \cap D_l = \emptyset$,

$1 \leq k, l \leq n_g, k \neq l$; (ii)$|D_k| \leq c(g_k)$, $1 \leq k \leq n_g$; (iii)$\sum_{k=1}^{n_g} \sum_{u \in D_k} dist(u, g_k)$ is minimized, where $dist(u, g_k)$ is the Euclidean distance between u and g_k.

We then assign each road with candidate active nodes. For $e \in E_r$, define $D(e) = \bigcup\{D_k | \text{if } g_k \text{ is on the road } e\}$. As a result, the set $\mathcal{CS}$ is partitioned into m_r disjoint sets, $D(e_1), D(e_2), \ldots, D(e_{m_r})$. And the *monitoring quality gain* of road $e \in E_r$ is obtained by using Eq.(3), denoted by $q(e)$.

4.3 Finding the distance-constrained tour

Recall that the MS starts from the depot in the roadmap, moves along roads with high quality gains, and returns to the depot, subject to the length constraint L. To find such a closed tour, we adopt the similar idea in [13]. That is, we convert this optimization problem into the distance-constrained shortest path problem, which has been extensively studied [14, 15].

We first construct a weighted, directed graph $G_M = (V_r, E_r, \omega, d)$. The weight of each edge $\langle p_i, p_j \rangle \in E_r$ is $\omega(p_i, p_j) = q(\langle p_i, p_j \rangle)$ and $d(p_i, p_j)$ is the Euclidean distance between p_i and p_j, where $p_i, p_j \in V_r$ are road intersections in roadmap M.

To find an optimal tour in $M = (V_r, E_r)$ is then reduced to find a closed path in G_M, starting from p_0 and ending at p_0, such that the total weight of the edges in the path is maximized, while the sum of the lengths of the edges in the path is bounded by L. We refer to this problem as *the distance-constrained longest path problem*, which however is NP-hard, since the well known NP-hard Hamiltonian problem [12] is a special case of the problem where no distance constraint is imposed.

We then instead propose a heuristic by converting the problem into a distance-constrained shortest path problem in another auxiliary directed graph $G'_M = (V_r, E_r, \omega', d)$. G'_M is constructed as follows. For each directed edge $\langle p_i, p_j \rangle \in E_M$,

$$\omega'(p_i, p_j) = \begin{cases} Q & \text{if } q(\langle p_i, p_j \rangle) = 0, \\ \frac{1}{q(\langle p_i, p_j \rangle)} - \rho & \text{otherwise} \end{cases} \quad (4)$$

where Q and ρ are positively large and small constants, $Q \geq q_{max}$, $0 < \rho \leq \frac{1}{q_{max}}$, and $q_{max} = \max_{e_l \in E_r}\{q(e_l)\}$. The purpose of introducing term ρ is to break the tie of two shortest paths between a pair of nodes with equal length by favoring the one with the larger quality gain. Let E_p be the set of edges in P. The distance-constrained shortest path problem in G'_M is to find a path P that consists of vertices in V_r, with p_0 as both its starting point and end point, such that $L(P) = \sum_{\langle p_i, p_j \rangle \in E_p} d(p_i, p_j) \leq L$ and $\sum_{\langle p_i, p_j \rangle \in E_p} \omega'(p_i, p_j)$ is minimized. There are several approximation algorithms for the distance-constrained shortest path problem. We modify the one by Chen *et al.* [15] for this problem, which consists of finding a feasible tour followed by local improvement to the found tour if possible.

4.3.1 Finding a feasible tour

We calculate all pairs of shortest paths for all pairs of nodes u and v in V_r, denoted by $SP(u, v)$. $P = \langle p_0 \rangle$ initially. Let $P = \langle p_0, p_1, \ldots, p_i, p_0 \rangle$ be the currently constructed path. We extend P by adding a next vertex u into P, which minimizes the total weight of the edges in the path

$$\sum_{j=0}^{i-1} \omega'(p_j, p_{j+1}) + \sum_{e_1 \in SP(p_i, u)} \omega'(e_1) + \sum_{e_2 \in SP(u, p_0)} \omega'(e_2), \quad (5)$$

subject to the constraint L

$$\sum_{j=0}^{i-1} d(p_j, p_{j+1}) + |SP(p_i, u)| + |SP(u, p_0)| \leq L. \quad (6)$$

All vertices in $SP(p_i, u)$ and $SP(u, p_0)$ should be added into P in order. The algorithm terminates when the length constraint is no longer met.

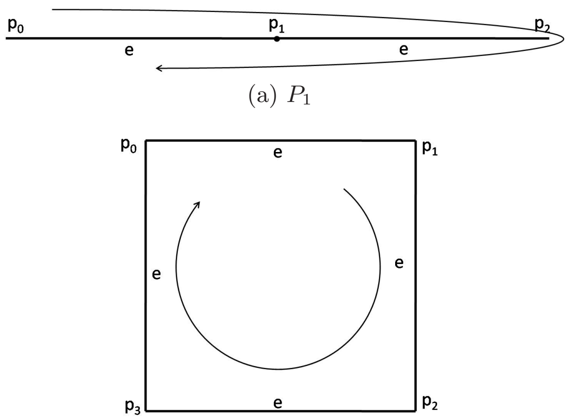
Note that $SP(p_i, u)$ and $SP(u, p_0)$ may contain vertices that have already been visited and included in P. Adding them again to P is, however, necessary. Otherwise, the MS may not be guaranteed to return to p_0 after visiting all other vertices in P. For instance, assume $P = \langle p_0, p_1, p_3, p_5, p_0 \rangle$ is the path to be extended, $SP(p_5, p_7) = \langle p_5, p_1, p_7 \rangle$, and $SP = \langle p_7, p_4, p_3, p_0 \rangle$. We now check whether adding p_7 to P still meets the L constraint. If we only consider to add un-visited vertices into P, the updated path will be $P = \langle p_0, p_1, p_3, p_5, p_7, p_4, p_0 \rangle$. Assume $L(P) \leq L$. Note that there is no edge connecting p_5 and p_7, or p_4 and p_0 in G'_M. In that case, after the MS visits p_5, it can not visit p_7 since $\langle p_5, p_7 \rangle \notin E_r$. In order to reach p_7, the MS has to visit other vertices not between p_5 and p_7 in P (p_1 in this example). Similarly, from p_4 to p_0, the MS has to visit p_3. Since $d(p_5, p_1) + d(p_1, p_7) \geq d(p_5, p_7)$ and $d(p_4, p_3) + d(p_3, p_0) \geq d(p_4, p_3)$, the actual tour length may exceed L. Therefore, we need to follow Eq.(6) to check whether the length constraint is met. And if yes, the updated path should be $P = \langle p_0, p_1, p_3, p_5, p_1, p_7, p_4, p_3, p_0 \rangle$.

4.3.2 Local improvement

Assume that a feasible tour $P = \langle p_0, p_1, \ldots, p_k, p_0 \rangle$ has been found. $E_p = \{\langle p_0, p_1 \rangle, \langle p_1, p_2 \rangle, \ldots, \langle p_k, p_0 \rangle\}$, $L(P) = \sum_{e \in E_p} dist(e) \leq L$, where $dist(e)$ is the Euclidean distance between two endpoints of e. We then perform a local improvement to the feasible solution by attempting to add more vertices to P as long as the length constraint is still met. To do so, we iteratively check whether there exists a vertex $p_j \notin P$ meeting the following conditions: (i) $\langle p_i, p_j \rangle \in E_r$ and $\langle p_j, p_{i+1} \rangle \in E_r$, where $\langle p_i, p_{i+1} \rangle \in E_p$, $i \neq 0$; (ii) $L(P) + d(p_i, p_j) + d(p_j, p_{i+1}) - d(p_i, p_{i+1}) \leq L$. If yes, add p_j into P since a better path $P = \langle p_0, p_1, \ldots, p_i, p_j, p_{i+1}, \ldots, p_k, p_0 \rangle$ is found. If there are multiple vertices meeting the length constraint, the one leading to the maximum quality gain will be added. This procedure continues until the L constraint is no longer met. The computational complexity of this local improvement is $O(n_r^2) = O(n^2)$.

$D_a = \bigcup_{e \in E_p} D(e)$ is the set of active nodes associated with path P. GW' is the set of gateways deployed on edges in E_p. The MS moves along E_p and collects the data generated from sensors in D_a by visiting gateways in GW'.

There may exist duplicate edges in the tour. In the above example, if the shortest path between p_7 and p_0 is $SP(p_7, p_0) = \langle p_7, p_1, p_3, p_0 \rangle$, the updated tour $P = \langle p_0, p_1, p_3, p_5, p_1, p_7, p_1, p_3, p_0 \rangle$, where edges $\langle p_1, p_3 \rangle$ and $\langle p_1, p_7 \rangle$ are visited twice. This will compromise the monitoring quality since the MS will not collect data when it moves along an edge which has been visited in the same tour. Consider two different tours with the same length in two roadmaps, shown in Fig. 3. P_1 is a round trip in which each edge is visited twice while in P_2, each edge is visited only once. Note that $L(P_1) = L(P_2) = 4 \cdot dist(e)$. Assuming the numbers of gateways on each edge in both P_1 and P_2 are identical, $|GW_1'| = \frac{1}{2} \cdot |GW_2'|$ and $|D_{a1}| = \frac{1}{2} \cdot |D_{a2}|$.



(a) P_1

(b) P_2

Figure 3: Two different tours with the same length

5. ENERGY-EFFICIENT DATA ROUTING

Having the closed tour P, the next stage is to route data generated from active nodes to corresponding gateways energy-efficiently. In this section, we aim to devise a routing protocol for this purpose. Assume an active node $v_i \in D_a$ is allocated to gateway g_k on road $e \in E_p$, with $dist(v_i, g_k) > r$. In that case, v_i cannot send its sensing data to g_k directly, rather, it needs at least one node acting as a relay node between them. Note that such relay nodes could be active nodes allocated to the same gateway, those allocated to other gateways, or inactive nodes.

We construct a weighted graph $G_w = (GW \cup V, E, \eta)$, where $\eta(u, v) = dist(u, v)$ for each $\langle u, v\rangle \in E$. We aim to construct a routing structure consisting of $|GW'|$ trees T_k rooted at g_k, $1 \le k \le |GW'|$. The routing tree T_k should span all active nodes in D_k and the $\sum_{\langle u,v\rangle \in T_k} \eta(u, v)$ is to be minimized. The problem of finding such a routing tree is then reduced to the Steiner Tree Problem (STP), with D_k as the *terminal set*. The STP is NP-hard, and in this paper, we find a solution to the problem by modifying the approximation algorithm by Kou *et al.* [16]. The algorithm is as follows.

First, compute all pairs of shortest paths in G_w. An auxiliary complete weighted graph G_{D_k} consisting of only D_k is constructed. The weight assigned to each edge in G_{D_k} is the length of the shortest path between the two endpoints of the edge in G_w. Second, find a minimum spanning tree (MST) in G_{D_k}. Let E_{OPT} be the set of edges in the MST. A subgraph of G_w, G_k, is induced by the edges in E_{OPT}. Note that each edge in E_{OPT} corresponds to a shortest path in G_w. Third, find a MST in the subgraph G_k, and prune those branches of the tree that do not contain the node in D_k. The resultant tree T_k is an approximate Steiner tree with D_k as the terminal set. Finally, assume that the set of vertices in the Steiner tree is V_{D_k}. For each $u \in V_{D_k}$, we increase weights of its associated edges in G_w by a small constant Δ_w. As a result, the opportunity of the same node involved by more than one Steiner trees is reduced and the energy consumption among sensors can be further balanced. The found Steiner trees T_k, $1 \le k \le |GW'|$, are used as routing trees for data collection. They form the routing structure $\mathcal{F}$.

Note that T_k rooted at g_k may include nodes not in D_k, and in that case, the number of descendants of g_k, $|V_{D_k}|$, will exceed $c(g_k)$. However, g_k is still able to fulfill the data relay task since it is only supposed to store data generated from sensors in D_k and upload them to the MS when the MS moves within its transmission range. Data generated from nodes in V_{D_k} but not in D_k is discarded.

The network lifetime is defined as the time of the first sensor's failure due to the depletion of its energy [21]. We only consider the energy consumption on wireless communication including data transmission and reception [22]. Let $c(v_i)$ be the number of nodes using v_i as the relay node in $\mathcal{F}$, and let $E_c(v_i)$ be the energy consumption of v_i in a tour.

$$E_c(v_i) = d_T(v_i) \cdot E_T(v_i, v_j) + d_R(v_i) \cdot E_R(v_i) \tag{7}$$

where $E_R(v_i)$ and $E_T(v_i, v_j)$ are the amounts of energy consumed by v_i on receiving 1 bit of data and transmitting 1 bit of data to v_j; $d_T(v_i)$ and $d_R(v_i)$ are respectively the amounts of data transmitted from and received by v_i in a tour.

$$E_R(v_i) = \epsilon_{elec} \tag{8}$$

$$E_T(v_i, v_j) = \epsilon_{elec} + \epsilon_{amp} \cdot dist^2(v_i, v_j), \tag{9}$$

where ϵ_{elec} is the energy cost of processing 1 bit data and ϵ_{amp} is the transmitter amplifier. Recall that $dist(v_i, v_j)$ is the Euclidean distance between v_i and v_j.

$$d_T(v_i) = \begin{cases} r_g \cdot (c(v_i) + 1) & \text{if } v_i \in D_a, \\ r_g \cdot c(v_i) & \text{otherwise} \end{cases} \tag{10}$$

$$d_R(v_i) = r_g \cdot c(v_i) \tag{11}$$

The network lifetime is

$$\frac{IE}{max\{E_c(v_i) \mid v_i \in V\}} \quad , \tag{12}$$

where IE is the initial energy capacity of sensors.

The heuristic including both the tour finding stage and the routing protocol designing stage is referred to as algorithm `Monitoring_Quality_Maximization`, or `MQM` for short.

6. PERFORMANCE EVALUATION

In this section, we evaluate the proposed algorithms through experiments. To evaluate the monitoring quality loss and the network lifetime, we vary network topologies, the deployment of gateways, and the length constraint L.

The roadmap in the monitoring area is shown in Fig. 4, in which there are 8 road intersections {A, B, C, D, E, F, G, H} and 13 roads. MS starts from `A` and will return to `A` at the end of each tour.

The parameter settings are listed in Table 1. We assume $I_k = 2 \cdot r$, $1 \le k \le n_g$. We adopt the energy consumption model in [20]. Also, we adopt the same way as [1] to generate sensing data in the range [0,100] and fix the ratio of training phase over the operation phase $R = P_t/P_o$ to be 10%. $P_o = 1000$ in our default simulation setting. All

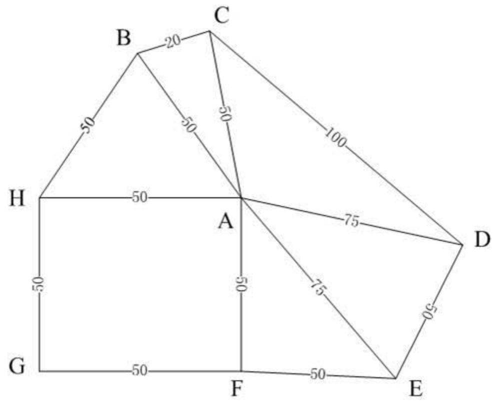
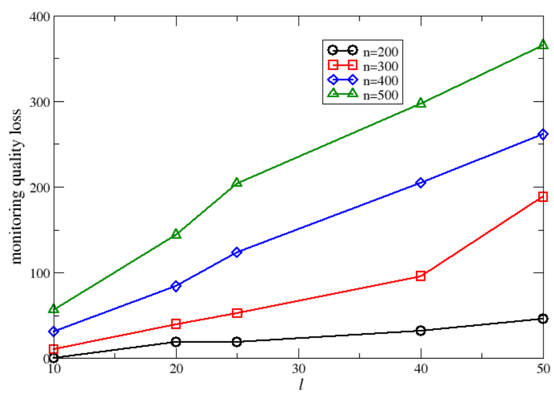
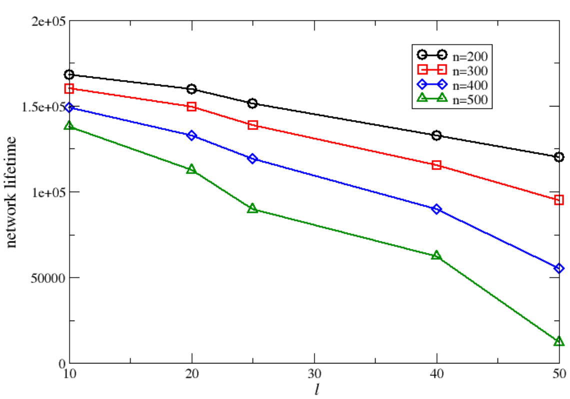


Figure 4: Monitoring region with the roadmap



(a) Monitoring quality loss with different gaps of gateways



(b) Network lifetime with different gaps of gateways

Figure 5: Network performance with different gateway deployments

Table 1: Simulation Setting

v	$2\ m/s$
r_k	$100\ bit/s$
r_g	$1\ bit/s$
r	$10\ m$
IE	$100\ Jules$
ϵ_{amp}	$100\ pJ/bit/m^2$
ϵ_{elec}	$50\ nJ/bit$

experiment results are the mean of results delivered by the algorithm with 50 different network topologies and identical parameter settings.

6.1 Impact of gateway deployment on the network performance

We first evaluate the monitoring quality and the network lifetime with different gateway deployments. In practice, we may install a gateway every l meters along roads in the roadmap, or deploy gateways according to the sensor density. In our simulations, we adopt the first way of gateway deployment and refer to l as the gap of gateways.

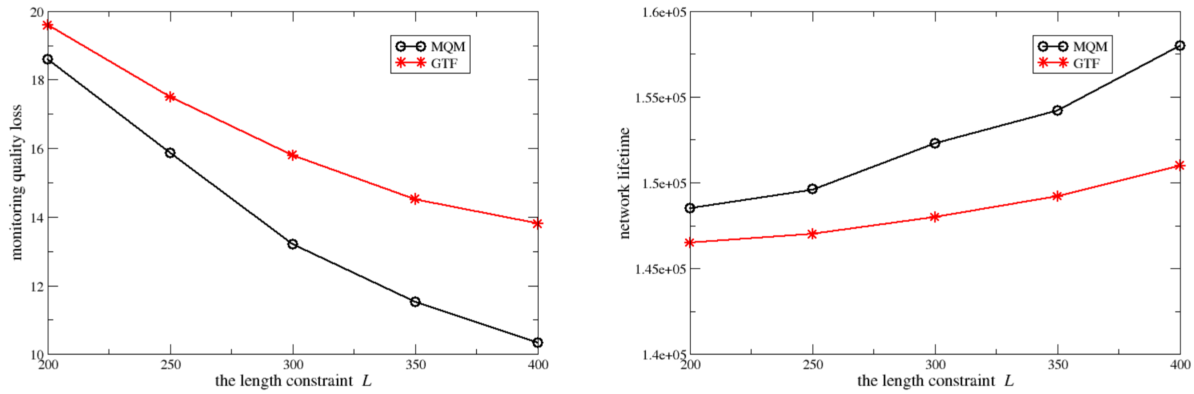
Fixing $n = 200$ and $L = 200$, we set l to be 10, 20, 25, 40, and 50 respectively. The quota of each gateway is 10 by Eq. (2). In Fig. 5(a), the curve with $n = 200$ shows the monitoring quality loss with different values of l. It indicates that the more densely the gateways deployed (the smaller the l), the smaller the monitoring quality loss. This is because more gateways will be able to relay data from more sensors to the MS. For example, when $l = 10$, the number of gateways the MS can visit is $200m/10m = 20$ and the total number of active nodes is $20 \times 10 = 200$, which is the set of all sensors. Thus, there is no monitoring quality loss. When l is set to be 20 and 25 respectively, the number of gateways the MS can visit are $200m/20m = 10$ and $200m/25m = 8$. And the corresponding numbers of active nodes are $10 \times 10 = 100$ and $8 \times 10 = 80$. Compared with the latter case, 100 active nodes will produce less quality loss, although sensing information loss is unavoidable in both cases. The curve with $n = 200$ in Fig. 5(b) demonstrates that with a smaller l, more gateways are able to distribute the data relay load evenly among sensors, resulting in a longer network lifetime.

In reality, the value of l is determined by both the user requirement on the monitoring quality and the budget of gateways. The number of gateways is $\lfloor L/l \rfloor$ and the gateway quota is $\frac{2r \cdot r_l}{L \cdot r_g}$ referring to Eq.(2). If the data transmission rates of all gateways are identical, the total number of active nodes is $\frac{L}{l} \cdot \frac{2r \cdot r_l}{L \cdot r_g} = \frac{2r \cdot r_l}{l \cdot r_g}$. That is, the number of active nodes only depends on l. If quality loss is not acceptable, gateways should be deployed every $\frac{2r \cdot r_l}{n \cdot r_g}$ meters on roads. If the budget for gateways is limited, we should increase l at the cost of larger monitoring quality loss.

6.2 Impact of network size on the network performance

We then investigate the network performance by varying n from 200 to 500, while keeping $L = 200$. The monitoring quality loss and the network lifetime are shown in Fig. 5(a) and (b), respectively.

From Fig. 5, we note that with constant l, a larger n leads to a greater quality loss and a shorter network lifetime.



(a) Monitoring quality loss with different L

(b) Network lifetime with different L

Figure 6: Performance evaluation with different length constraints

This is because the same number of active nodes can better represent the other nodes when the network size is smaller. Also, with the increase of network size n, more energy will be consumed on the data collection, resulting in a shorter network lifetime.

6.3 Impact of tour length constraint on the network performance

We next evaluate the network performance by varying the length constraint L from 200 to 400 with the increment of 50 while fixing $l = 25$ and $n = 200$. In Fig. 6, curve `MQM` shows the monitoring quality loss and the network lifetime with various L. Generally, larger L results in better network performance.

As discussed above, the number of active nodes is irrelevant to L. However, different settings of L do impact the network performance in the following two aspects. First, in terms of data freshness. Larger L causes a longer data delivery latency. With $L = 200m$, e.g., the MS collects data generated within the last $\frac{200m}{2m/s} = 100s$ while with $L = 400m$, the collected data is generated within the last $\frac{400m}{2m/s} = 200s$. Second, in the solution domain. Larger L enlarges the domain for a better solution in terms of less monitoring quality loss, and more energy-efficient data collection. With $l = 25$, the number of active nodes is 80 regardless of the value of L. Setting L to be 200 and 400, e.g., the numbers of gateways the MS can visit are 8 and 16, with quotas 10 and 5 respectively ($8 \times 10 = 16 \times 5 = 80$). However, compared to $L = 200$, the scenario with $L = 400$ explores the roadmap with more relaxing constraint, thus is more likely to involve edges with higher monitoring quality gains and distribute the data relay load more evenly among sensors.

6.4 Performance comparison

We finally compare the performance of algorithm `MQM` with that of a greedy heuristic. The greedy heuristic consists of two stages as well. The only difference between them lies in the tour finding stage after assigning each road with a monitoring quality gain in the auxiliary graph G_M. Let $P = \langle p_0, p_1, \ldots, p_l, p_0 \rangle$ be the tour generated so far. The next vertex to be added to P is determined as follows. The algorithm first checks all un-visited neighboring vertices of p_l in G_M and adds p_k between p_l and p_0 in P if it meets: (i) $p_k \notin P$; (ii) $q(\langle l, k\rangle) = max\{q(\langle l, i\rangle) | \langle l, i\rangle \in E_r\}$; and (iii) $|SP(p_k, p_0)| + d(p_l, p_k) + L(P) - d(p_l, p_0) \leq L$. If no such a vertex is found, the algorithm checks all visited neighboring vertices of p_l, finds $p_k \in P$ with the minimum $|SP(p_k, p_0)| + d(p_l, p_k) + L(P) - d(p_l, p_0)$ $(\leq L)$, and adds it between p_l and p_0 in P. The algorithm terminates if the L constraint is no longer met. We refer to this heuristic as algorithm `Greedy_Tour_Finding`, or `GTF` for short.

We compare the network performance delivered by algorithm `MQM` and `GTF` by fixing $n = 200$, $l = 25$, and varying L from 200 to 400 with the increment of 50. The monitoring quality loss and the network lifetime delivered by two algorithms are shown in Fig. 6(a) and Fig. 6(b) respectively. From the figures we can notice that algorithm `MQM` always outperforms algorithm `GTF` and with the increase of L, the performance gap between them becomes larger and larger.

7. CONCLUSION

In this paper, the problem of optimizing the monitoring quality using a mobile sink has been considered. The mobile sink has been assumed to move in a given roadmap for collecting the data generated from some sensors by visiting the gateways. We have formulated the problem as a joint optimization problem that aims to find a closed tour for the mobile sink to minimize the monitoring quality loss, and to design an energy-efficient routing protocol for data collection. We have proposed a novel two-stage heuristic for it. We also evaluated the performance of the proposed algorithms against another heuristic by simulation. The experimental results demonstrate that the proposed algorithms always outperform the other one.

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