This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

Prolonging Network Lifetime via A Controlled Mobile Sink in Wireless Sensor Networks

Weifa Liang
School of Computer Science
Australian National University
Canberra, ACT 0200, Australia
Email:wliang@cs.anu.edu.au

Jun Luo
School of Computer Science
National University of Defense Technology
Changsha, Hunan, P. R. China
Email:junluo@nudt.edu.cn

Xu Xu
School of Computer Science
Australian National University
Canberra, ACT 0200, Australia
Email:grace.xu@cs.anu.edu.au

***Abstract*—In this paper we explore the mobility of a mobile sink in a wireless sensor network (WSN) to prolong the network lifetime. Since the mechanical movement of mobile sink is driven by petrol and/or electricity, the total travel distance of the mobile sink should be bounded. To minimize the data loss during the transition of the mobile sink from its current location to its next location, its moving distance must be restricted. Also, considering the overhead on a routing tree construction at each sojourn location of the mobile sink, it is required that the mobile sink sojourns for at least a certain amount of time at each of its sojourn locations. The distance constrained mobile sink problem in a WSN is to find an optimal sojourn tour for the mobile sink such that the sum of sojourn times in the tour is maximized, subject to the above mentioned constraints. In this paper we first formulate the problem as a mixed integer linear programming (MILP). Due to its NP-hardness, we then devise a novel heuristic for it. We finally conduct extensive experiments by simulations to evaluate the performance of the proposed algorithm in terms of network lifetime. The experimental results demonstrate that the solution delivered by the proposed heuristic is nearly optimal which is comparable with the one by solving the MILP formulation but with much shorter running time.**

I. INTRODUCTION

Wireless sensor networks (WSNs) consist of hundreds to thousands of battery-powered tiny sensors that are endowed with a multitude of sensing modalities including environmental monitoring and security surveillance purposes [1]. Although there have been significant progress in sensor fabrications including processing design and computing, advances of battery technology still lag behind, making energy resource the fundamental constraint. To maximize the network lifetime, energy conservation is of paramount importance in WSNs.

Most existing studies assume that the sink (the base station) in WSNs is static, which is a gateway between the sensor network and users, and all sensing data from the sensors are relayed to it through multi-hop relays. As a result, the sensors near to the sink become the bottlenecks of energy consumption since they have to relay the data for other remote sensors. Once they deplete their energy, the sink will be disconnected from the rest of the network while the rest of sensors are still fully operational with sufficient residual energy. To mitigate this *static sink neighborhood problem*, new strategies have been developed by exploiting the mobility of a sink to better balance the energy consumption among the sensors. That is, the mobile sink traverses the monitoring region and sojourn at some locations to collect sensed data. It has been demonstrated that sink mobility is a blessing rather than a curse to network performance including the network lifetime, scalability, and throughput, etc [8], [14], [3], [10], [11], [13].

Recent works on exploiting the mobility of a sink for network lifetime prolongation considered several *bottleneck* constraints imposed on the mobile sink [11], [3]. These constraints include the maximum number of sojourn locations [11], the maximum distance between two consecutive movements, and the minimum sojourn time at each sojourn location [3]. However, they all ignored one important *additive* constraint. That is, the mobile sink is mechanically driven by either petrol or electricity. Thus, its total travel distance per tour must be bounded. To incorporate this additive constraint into the problem formulation makes the problem much more realistic but challenging. In this paper we consider a joint optimization problem under both additive and bottleneck constraints, which consists of determining the optimal sojourn tour for the mobile sink and scheduling its sojourn time at each chosen sojourn location such that the network lifetime is maximized, provided that the following constraints imposed on the mobile sink are met, its total travel distance, the maximum distance between its two consecutive movements, and its minimum sojourn time at each sojourn location. We refer to this problem as *the distance-constrained mobile sink problem*.

Our major contributions in this paper are as follows. We first formulate a joint optimization problem, referred to as the distance-constrained mobile sink problem, by providing a mixed integer linear programming solution. Due to its NP-hardness, we then propose a novel three-stage heuristic that exhibits low computational complexity and high scalability. That is, it first calculates the sojourn time profile at each potential sojourn location. It then finds a feasible sojourn

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

tour for the mobile sink such that the sum of sojourn times at the chosen sojourn locations is maximized, subject to the mentioned constraints. It finally makes a sojourn time scheduling for the mobile sink by determining its exact sojourn time at each chosen sojourn location. We finally conduct experimental evaluation by simulations. The experimental results demonstrate the solution delivered by the heuristic is nearly the optimal, while the heuristic only takes a small fraction of running time of the MILP formulation of the problem.

The rest of the paper is organized as follows. Section II discusses the related work. Section III introduces the system model and defines the problem. Section IV formulates the problem a mixed integer linear program. Section V proposes a novel heuristic algorithm for it, and Section VI evaluates the performance of the proposed algorithm through experimental simulations. Section VII concludes the paper.

II. Related work

The mobility of a mobile sink can be classified into *uncontrolled mobility* [14], [13], and *controlled mobility* [10], [11], [2], [3]. For the former, the mobile sink can move randomly in the monitored region, while for the latter it can only move along the pre-defined trajectory. The recent breakthrough on *uncontrolled mobility* showed that if a sink must sojourn at each location of a given set of locations, there is a polynomial solution to maximize the network lifetime [13]. However, handling the *controlled mobility* is much more challenging and needs more efforts.

The first attempt on *controlled mobility* was made by Gandham *et al.* in [8]. They presented an ILP (integer linear program) model to determine the locations of multiple mobile sinks, the model aims at minimizing the energy consumption per node and the total energy consumption within each round. They assumed that the multiple sink mobility is scheduled round by round. Within a round, the mobile sinks are stationary and assigned the same amounts of sojourn time. They are allowed to be mobile only during the transition period from the current round to the next round. Luo and Hubaux [10] assumed sensors are uniformly deployed into a circle region by formulating the network lifetime maximization problem into a min-max problem. They concluded that keeping the sink moving along the external perimeter of the circle will achieve a much longer network lifetime in comparison with the case when the sink stays at the center of the circle. Wang *et al* [14] considered a joint optimization problem of determining the sink movement and its sojourn time at certain network nodes in a grid network so that the network lifetime is maximized. On this special network, they proposed an ILP solution for the problem, assuming that a half of work load (the number of messages generated and received) of each node flow along its horizontal and vertical links towards the current location of the mobile sink. Although such flow-based routing approaches are very attractive theoretically, they may not be suitable for the real sensor networks due to the difficulty on the flow control and its computational infeasibility with the growth of network size. Luo *et al.* [11] addressed the joint optimization problem by proposing a two-stage scheduling. It calculates the sojourn time of the sink at each "anchor" point and filtered out those points at which the sojourn times are below the given threshold, followed by determining the exact sojourn time at each chosen anchor point. Basagni *et al.* [3] recently developed a more realistic model by incorporating two realistic *bottleneck* constraints on the mobile sink: the maximum distance between its two consecutive movements and the minimum sojourn time at each sojourn location. Under these constraints, they aim to find an optimal sojourn tour for the mobile sink such that the network lifetime is maximized. They formulated the problem by a mixed integer linear program and proposed a distributed heuristic for it.

III. Preliminaries

We consider a wireless sensor network $G(V, E)$ consisting of n stationary sensors and a mobile sink, where V is the set of sensors and E is the set of links. There is a link between two sensors, or a sensor and the sink, if they are within the transmission range of each other. The network lifetime is defined as the time of the first sensor's failure due to the depletion of its energy [5]. We only consider the energy consumption on data transmission and reception [12]. The location information of sensors is fixed and known a priori. All sensors have the same data generation rate r. We assume that the mobile sink has unlimited energy supplies in comparison with the energy capacity of sensors. However, the mobile sink is mechanically driven by petrol or electricity, thus, its total travel distance is proportional to the energy it has. The sink starts from and returns to a location v_0 to recharge petrol or electricity. The location v_0 may be outside of the monitored region. During its sojourn tour, the mobile sink sojourns at each chosen location for a certain duration in order to collect the sensing data from all sensors via a routing tree rooted at the location. Assume that the potential sojourn locations of the mobile sink are exactly the locations of n sensors. We denote $nc_{v_i}(v_j)$ as the number of descendants of sensor v_j in a routing tree rooted at the sink located at v_i. Notice that a node is a descendant of itself. The energy consumption of sensor v_j by relaying data per time unit is as follows.

$$ec_{v_i}(v_j) = e_r \cdot (nc_{v_i}(v_j) - 1) \cdot r + e_t \cdot ndc_{v_i}(v_j) \cdot r \quad (1)$$

where e_r and e_t are the energy consumptions by transmitting and receiving 1-bit data, respectively. It can be seen that the value of $ec_{v_i}(v_j)$ is closely related to the value of $nc_{v_i}(v_j)$, the former is proportional to the latter.

The distance-constrained mobile sink problem in a WSN thus is to find an optimal sojourn tour starting from and ending to the same location such that the network lifetime is maximized, subject to the following important constraints imposed on the mobile sink: (i) its total travel distance per tour must be bounded by a given value L, as the mobile sink is mechanically driven by petrol or electricity. (ii) When the sink moves from one location to the next, sensors have to buffer their sensed data locally until it arrives its next location for data gathering. To minimize the data loss due to the buffer overflow during this duration, the maximum distance between its two consecutive movements must be bounded by R_{max}. (iii) A routing tree rooted at each sojourn location will be built and the sink sojourns at that location for a certain amount of time. Whenever it moves to another location, the routing tree will have to be re-constructed, causing extra energy consumption. Therefore, to make each of its motion to be profitable, it is required that the mobile sink sojourns at each of its sojourn locations for at least T_{min} time units. Notice that the sum of sojourn times of the mobile sink at each sojourn location in the tour is actually the network lifetime. Therefore, the problem of prolonging the network lifetime is actually to find a sojourn tour for the mobile sink such that the sum of its sojourn times is maximized, subject to the above constraints. Specifically, let $v_1, v_2, \ldots, v_k$ be the set of visited locations (sensors) by the mobile sink, $1 \leq k \leq n$, and let t_i be the sojourn time of the sink at the location of sensor v_i, $1 \leq i \leq k$. Our objective is to find such a set of k sojourn locations and the corresponding sojourn times to maximize $\sum_{i=1}^{k} t_i$, provided the following constraints are met: $\sum_{i=0}^{k-1} d(v_i, v_{i+1}) + d(v_k, v_0) \leq L$, $d(v_i, v_{i+1}) \leq R_{max}$, and $t_i \geq T_{min}$ for each v_i, $1 \leq i \leq k$, where $d(v, u)$ is the Euclidean distance between sensors v and u.

IV. Mixed Integer Linear Program

We first define some parameters and variables as follows.

- $\text{IE}(v_j)$: the current residual energy of sensor v_j, all sensors have the same energy capacity IE initially.
- $ec_{v_i}(v_j)$: the amount of energy consumption of sensor v_j per time unit in the routing tree rooted at location v_i.
- $y_j \in \{0, 1\}$, $y_j = 1$ if the location of sensor v_j is a sojourn location of the sink; otherwise, $y_j = 0$, $1 \leq j \leq n$.
- $x_{i,j} \in \{0, 1\}$, $x_{i,j} = 1$ if the sink moves from its current location v_i to the next v_j, $0 \leq i, j \leq n$.
- $z_i > 0$ is an integer ranged from 1 to n which is the rank of sensor v_i and $t_i > 0$, $1 \leq i \leq n$.
- T_{min} and T_{max} are given positive constants.

We then formulate the problem as the following mixed integer linear program.

$$Maximize \qquad \sum_{i=1}^{n} t_i \tag{2}$$

subject to:

$$\sum_{v_i \in V} ec_{v_i}(v_j) t_i \leq \text{IE}(v_j), \quad \text{for any } v_j \in V \tag{3}$$

$$\sum_{i=1}^{n} x_{i,j} = \sum_{j=1}^{n} x_{i,j}, \quad \text{for all } i,\ 0 \leq i \leq n \tag{4}$$

$$\sum_{i=1}^{n} x_{0,i} = 1, \quad \text{for any } v_i \in V \tag{5}$$

$$\sum_{i=1}^{n} x_{i,0} = 1, \quad \text{for any } v_i \in V \tag{6}$$

$$\sum_{i=0}^{n} x_{i,j} = y_j, \quad \text{for any } v_j \in V \tag{7}$$

$$T_{min} \cdot y_i \leq t_i \leq T_{max} \cdot y_i, \quad \text{for any } v_i \in V \tag{8}$$

$$\sum_{i=0}^{n} \sum_{j=0}^{n} d_{i,j} x_{i,j} \leq L \tag{9}$$

$$d_{i,j} x_{i,j} \leq R_{max}, \quad \text{for all } i \text{ and } j,\ 1 \leq i, j \leq n \tag{10}$$

$$z_j - z_i + n x_{i,j} \leq n - 1, \quad \text{for any } 1 \leq i, j \leq n \tag{11}$$

$$x_{i,j} \in \{0, 1\}, \quad \text{for any } 0 \leq i, j \leq n \tag{12}$$

$$y_i \in \{0, 1\}, \quad \text{for any } v_i \in V \tag{13}$$

$$t_i \geq 0, \quad \text{for any } i,\ 1 \leq i \leq n \tag{14}$$

$$z_i \geq 0, \quad \text{for any } i,\ 1 \leq i \leq n \tag{15}$$

The objective (2) is to maximize the network lifetime. Constraint (3) ensures that the total energy consumption by any sensor v_j during the network lifetime is no more than its energy, while Equation (4) forces flow conservation at all sojourning locations of the sink. Equations (5) and (6) imply that the sink starts from and ends at location v_0. Equation (7) implies that there is at most only one incoming edge into sensor v_j if v_j is a sojourn location of the sink. Constraint (8) forces that the minimum sojourn time of the sink at a location v_j is at least T_{min}. Constraint (9) ensures that the total distance of the sojourn tour by the mobile sink is no more than L. Constraint (10) ensures that the distance of the sink between its two consecutive movements is no more than R_{max}. Constraint (11) prevents the formation of disjoint cycles that do not contain the starting point v_0. Associated with each sensor v_i, there is a unique rank z_i whose value is ranged from 1 to n. If both sensors v_i and v_j are in the sojourn tour and v_i is visited prior to v_j, then the rank of v_i is smaller than that of v_j, *i.e.*, $z_i < z_j$. Inequality (11) ensures that there are no other cycles in the solution except the only one containing v_0. It can be seen that the problem is NP-hard because the distance-constrained shortest path problem is NP-complete [9], which is a special case of this problem by assuming the sojourn time at each potential sojourn location is given.

V. Heuristic algorithm

With the growth of network size, it becomes computationally infeasible to solve the mixed integer program. In this section we propose a scalable heuristic for the distance-constrained mobile sink problem, which consists of the following three stages. The sojourn time profile at each potential location is calculated first. Based on the sojourn time profiles, it then finds a feasible sojourn tour for the mobile sink by identifying the sojourn locations such that the sum of the sojourn times is maximized, subject to the specified constraints. It finally determines the exact sojourn time at each chosen sojourn location, and the sum of these sojourn times is the network lifetime.

A. The sojourn time of the sink at the location of each sensor

Following the assumption that the location of each sensor is a potential sojourn location of the sink. To calculate the sojourn time t_i of the mobile sink at each potential location v_i, we assume that a Breadth-First-Search (BFS) routing tree rooted at v_i is constructed. Let T_v be the tree rooted at the location $v \in V$ and $c_v(u)$ be the number of descendants of sensor $u \in V$ in the tree T_v. The network lifetime maximization problem without any constraints is to

$$maximize \quad \sum_{i=1}^{n} t_i, \tag{16}$$

subject to

$$\sum_{i=1}^{n} ec_{v_i}(v_j) t_i \leq \mathrm{IE}(v_j), \text{ for all } \ j \ , 1 \leq j \leq n \tag{17}$$

Note that the above linear programming is polynomially solvable.

B. Identify the sojourn tour of the mobile sink

To identify the sojourn tour of the sink, we construct a weighted, directed graph $G_D = (V_D, E_D, \omega, d)$, where $V_D = \{v_{i,1}, v_{i,2} \mid v_i \in V\}$. Associated with each sensor $v_i \in V$, there are two corresponding nodes $v_{i,1}$ and $v_{i,2}$ in G_D and there is a directed edge in E_D from $v_{i,1}$ to $v_{i,2}$ with weight $\omega(v_{i,1}, v_{i,2}) = t_i$ and $d(v_{i,1}, v_{i,2}) = 0$. There is a directed edge $\langle v_{i,2}, v_{j,1} \rangle$ in E_D from $v_{i,2}$ to $v_{j,1}$ if $d(v_i, v_j) \leq R_{max}$ and $t_j \geq T_{min}$. The associated weight is $\omega(v_{i,2}, v_{j,1}) = 0$ and $d(v_{i,2}, v_{j,1}) = d(v_i, v_j)$. The distance between the two endpoints of any link in E_D is no more than R_{max}, except that the one from v_0 to its first sojourn location and from the last sojourn location to v_0.

To find an optimal sojourn tour in $G(V, E)$ for the mobile sink starting from v_0 and returning to v_0 is then reduced to find a path in G_D from a source node $v_{i,1}$ to a destination node $v_{j,2}$ such that the total weights of the edges in the path is maximized, while the sum of the distances of the edges in the path is bounded. We refer to this problem as *the distance-constrained longest path problem*, which however is NP-hard, since the well known Hamiltonian cycle problem is one of its special cases where no distance constraint is imposed. We instead propose a heuristic for it.

We first transform the problem into a distance-constrained shortest path problem in another auxiliary directed graph $G'_D = (V_D, E_D, \omega', d)$, which will return a feasible solution to the former. G'_D is defined as follows. For each directed edge $\langle v_{i,1}, v_{i,2} \rangle \in E_D$,

$$\omega'(v_{i,1}, v_{i,2}) = \begin{cases} M, & \text{if } t_i = 0 \\ \frac{1}{t_i} - \rho, & \text{otherwise} \end{cases}$$

and for each $\langle v_{i,2}, v_{j,1} \rangle \in E_D$, $\omega'(v_{i,2}, v_{j,1}) = 0$, where M and ρ are positively large and small constants, $M \geq t_{max}$, $0 < \rho \leq \frac{1}{t_{max}}$, and $t_{max} = \max_{1 \leq i \leq n}\{t_i\}$. The purpose of introducing term ρ is to break a tie of two shortest paths between a pair of nodes with equal length by favoring the one with a longer sojourn time. The distance-constrained shortest path problem in G'_D is to find a path in G'_D from a source node $v_{i,1}$ to a destination node $v_{j,2}$ such that the weighted sum of the edges in the path is minimized, while the sum of distances of all edges in the path is no greater than $L - d(v_0, v_i) - d(v_0, v_j)$. There are several approximation algorithms for it, we will adopt the one given by Chen *et al.* [6]. Assume that a feasible sojourn tour $P = \langle v_0, v_1, \ldots, v_k, v_0 \rangle$ for the mobile sink has been found. then, $D(P) = \sum_{i=0}^{k} d(v_i, v_{i+1}) \leq L$.

We then perform a local improvement to the feasible solution by adding more sojourn locations into the sojourn tour P as long as the specified constraints are still met. To do so, we iteratively check whether there is a location $v_j \notin P$, $t_j \geq T_{min}$, and an existing location $v_i \in P$, $i \neq 0$, such that $d(v_j, v_i) \leq R_{max}$, $d(v_j, v_{i+1}) \leq R_{max}$, and $D(P) + d(v_j, v_i) + d(v_j, v_{i+1}) - d(v_i, v_{i+1}) \leq L$. If yes, add v_j into P and a better path $P' = \langle v_0, v_1, v_2, \ldots, v_i, v_j, v_{i+1}, v_{i+2}, \ldots, v_k, v_0 \rangle$ is found. If there are multiple locations to meet the mentioned constraints, the one with the maximum sojourn time t_j will be added. This procedure continues until one of the constraints is no longer met. The computational complexity of this local improvement is $O(n^2)$.

C. Calculation of the sojourn time at each sojourn location

Having the found sojourn tour for the mobile sink, the actual sojourn time t'_i at each $v_i \in P = \langle v_0, v_1, \ldots, v_k, v_0 \rangle$ will be re-calculated in stage three. The sojourn time t_i calculated at stage one is based on the involvement of all potential locations. Now, the mobile sink only sojourns at these chosen locations in P only. We expect it will have a longer network lifetime in comparison with the one based on the sojourn time profile. It proceeds in a number of iterations. Within each iteration, t_i is increased by the amount of Δt such that the minimum residual energy among the sensors is maximized after sojourning at v_i with extra Δt time units. This procedure continues until the residual energy of a sensor becomes zero. Notice that the number

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

of iterations is closely related to the granularity of Δt. The larger the value of Δt, the fewer times the number of iterations. As a result, the actual sojourn time at each $v_i \in P$ is calculated. And the network lifetime is $\sum_{i=i}^{k} t'_i$. For convenience, we refer to the above proposed heuristic as algorithm CSPLI.

VI. Performance Evaluation

In this section we evaluate the performance of the proposed heuristic algorithm and investigate the impact of constraint parameters R_{max}, L and T_{min} on the network lifetime through experimental simulations.

A. Simulation environment

We consider a wireless sensor network consisting of from 20 to 400 sensors which are randomly deployed in a $200m \times 150m$ rectangle region. The transmission range R of each sensor is fixed to 25 meters and its initial energy capacity IE is $50Jules$. We assume that the data generation rate of sensors is $r = 4bits/s$. We further assume that $(0, 0)$ is the center coordinate of the monitoring region. The mobile sink is initially located at $(150, 100)$, outside of the monitoring region. The Breadth-First-Search tree is used for data collection. In all our experiments we adopt the energy consumption parameters of real sensors - MICA2 motes [7], where $e_t = 14.4 \times 10^{-6} J/bit$ and $e_r = 5.76 \times 10^{-6} J/bit$. The value in each figure is the average of the results by applying each mentioned algorithm to five different network topologies of the same size.

To evaluate the performance of the proposed algorithm, we introduce one of its variants, referred to as a greedy heuristic, consisting of three stages as well. The only difference between them lies in stage two. The greedy heuristic lists all sojourn potential locations $v_1, v_2, \ldots, v_n$ in increasing order of their sojourn time profile, i.e., $t_i \geq t_{i+1}$, $1 \leq i \leq n-1$. The sojourn tour P is initially empty, and it is expanded greedily by adding the locations in the sorted sequence. Assume that the first $j-1$ locations of in the sequence have been checked and $P = \langle s_1, s_2, \ldots, s_l \rangle$ is the current sojourn tour of the mobile sink. We now explore the next location v_j by checking whether the following constraints are met. $t_j \geq T_{min}$, $d(s_l, v_j) \leq R_{max}$, and $D(P_{v_0,s_l}) + d(s_l, v_j) + d(v_j, v_0) \leq L$. If so, P is updated and $P = \langle s_1, s_2, \ldots, s_l, v_j \rangle$. Otherwise, it explores the next location v_{j+1}, and so on. After examining all locations in the sorted sequence, P has been constructed. We refer to this greedy heuristic as algorithm Sorted_Short_Tour or SST for short.

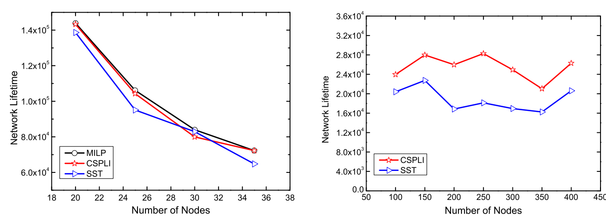
B. Performance evaluation of the proposed heuristic

We first investigate the scalability of MILP, CSPLI and SST, which can be seen from Table I. The running time is obtained on a Pentium 4 3.2GHz machine with 1GB RAM. Table I indicates that with the growth of network size, the

Table I
THE RUNNING TIME (IN SECONDS) OF THREE ALGORITHMS

Size n	20	25	30	35	100	200
MILP	233.91	1,992.30	7,882.85	34,687.16	-	-
CSPLI	1.24	1.44	1.95	2.76	20.84	176.59
SST	0.98	1.17	1.67	2.59	22.00	180.80

running time of MILP becomes prohibitively long when the network size reaches a moderate size. For example, when the network size is 35, it takes 9.65 hours to solve the MILP. We here use lp_solve software package [4] to solve the MILP. In contrast, both heuristics exhibit the high scalability, which take only several minutes even when the network size reaches several hundreds.



(a) MILP, CSPLI, SST　　(b) CSPLI VS. SST

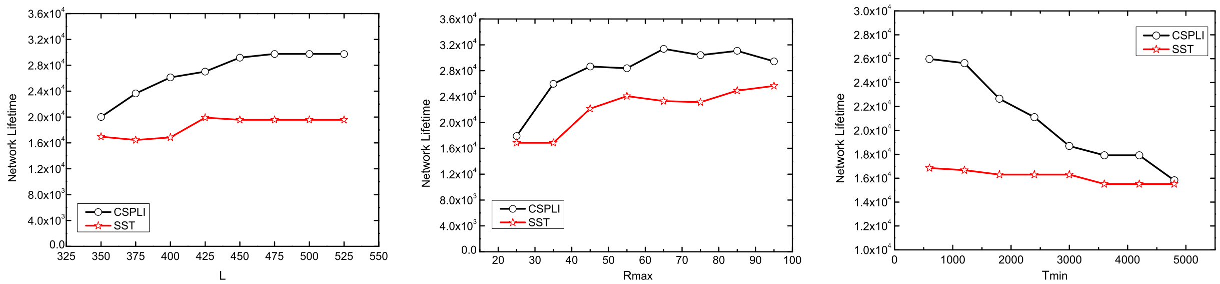
Figure 1. Network lifetimes delivered by different algorithm

We then evaluate the performance of algorithms CSPLI and SST in comparison with that of the exact algorithm MILP. Fig. 1(a) plots the network lifetimes by the MILP formulation and algorithms CSPLI and SST when the network size varies from 20 to 35 under the constraints $R_{max} = 35$ meters, $L = 400$ meters, and T_{min}=600 seconds. It can be seen that the performance of algorithm CSPLI is nearly optimal, which is very close to the optimal one when the network size is no greater than 35. Also, although algorithm SST is inferior to algorithm CSPLI, it still achieves around 90% of the performance of the optimal one. Overall, the performance of both heuristics are around 98.37% and 94.13% of the optimal one on average.

We thirdly evaluate the performance of algorithms CSPLI and SST by varying the network size from 100 to 400 while keeping the other constraint parameters unchanged. Fig. 1(b) shows that algorithm CSPLI outperforms algorithm SST significantly in the prolongation of network lifetime.

C. Impact of constraint parameters on network lifetime

We finally study the impact of constraint parameters R_{max}, L, and T_{min} on the network lifetime by assuming the network size being fixed as $n = 200$. R_{max} and L reflect the flexibility of the mobile sink to choose its next sojourn location and its total travel distance per tour. Intuitively, larger values of R_{max} and L result in a longer network lifetime. Similarly, a smaller value of T_{min} implies that the energy consumption can be better balanced among the



(a) $R_{max} = 35m$, $T_{min} = 600s$ (b) $L = 400m$, $T_{min} = 600s$ (c) $R_{max} = 400m$, $L = 35m$

Figure 2. The impact of various constraint parameters on the network lifetime

sensors through the frequent movement of the mobile sink, thereby leading to a longer network lifetime.

Fig. 2(a) plots the network lifetimes delivered by various algorithms by varying the value of L from 350 to 525 meters while keeping $R_{max} = 35m$ and $T_{min} = 600s$ to be fixed. With the growth of L, the performance gap between algorithm `CSPLI` and algorithm `SST` increases too. However, this improvement by increasing L is not unlimited, any further improvement becomes insignificant when L reaches 475 meters for algorithm `CSPLI` and 425 meters for algorithm `SST`. Fig. 2(b) illustrates the impact of R_{max} on the network lifetime by varying it from 25 to 75 meters, while keeping $L = 400m$ and $T_{min} = 600s$ to be fixed. It can be seen that although R_{max} does affect the network lifetime, this effect becomes diminishing with any further increases. Fig. 2(c) plots the network lifetime curves by varying T_{min} from 600 to 4,800 seconds while keeping $R_{max} = 35m$ and $L = 400m$ to be fixed. It implies that the network lifetime decreases, with the increase of T_{min}. Moreover, a sufficiently large T_{min} may result in a sojourn tour consisting of one sojourn location only. It also implies that if the overhead on the construction of routing trees is excessive, it is better for the sink to be stationary rather than mobile.

VII. Conclusions

In this paper we have studied the problem of prolonging network lifetime using the mobile sink subject to several constraints imposed on the mobile sink. These include the total tour distance, the maximum distance between its two consecutive movements, and the minimum sojourn time at each sojourn location. We first provided a mixed integer linear programming solution to this multiple-constrained, joint optimization problem. Due to its high complexity and poor scalability, we then propose a novel heuristic for it. We finally conducted extensive experiments by simulations to evaluate the performance of the proposed algorithm in comparison with the optimal solution by solving the MILP. The experimental results demonstrated that the solution delivered by the proposed algorithm is the nearly optimal, and comparable with the MILP formulation but with much shorter running time.

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks*, Vol. 38, pp. 393–422, 2002.

[2] S. Basagni, A. Carosi, E. Melachrinoudis, C. Petrioli, and Z. M. Wang. A new MILP formulation and distributed protocols for wireless sensor networks lifetime maximization. *Proc. of ICC'06*, IEEE, pp. 3517–3524, 2006.

[3] S. Basagni *et al*. Controlled sink mobility for prolonging wireless sensor networks lifetime. *Wireless Networks*, Vol. 14, pp.831–858, 2008.

[4] URL:http://lpsolve.sourceforge.net/5.5/

[5] J-H Chang and L. Tassiulas. Energy conserving routing in wireless ad hoc networks. *Proc. INFOCOM'00*, IEEE, 2000.

[6] S. Chen, M. Song, and S. Sahni. Two techniques for fast computation of constrained shortest paths. *IEEE/ACM Trans Networking*, Vol.16, pp.105–114, 2008.

[7] Crossbow Inc. MPR-Mote Processor Radio Board User's Manual.

[8] S. R. Gandham, M. Dawande, R. Prakask, and S. Venkatesan. Energy efficient schemes for wireless sensor networks with multiple mobile base stations. *Proc. Globecom'03*, IEEE, 2003.

[9] M. R. Garey and D. S. Johnson. *Computers and Intractability: A guide to the Theory of NP-Completeness*. W.H. Freeman and Company, NY, 1979.

[10] J. Luo and J-P Hubaux. Joint mobility and routing for lifetime elongation in wireless sensor networks. *Proc of INFOCOM'05*, IEEE, 2005.

[11] J. Luo, J. Panchard, M. Piorkowski, M. Grossblauser, and J-P Hubaux. Mobiroute: routing towards a mobile sink for improving lifetime in sensor networks. *Proc of DCOSS'06*, LNCS, Vol. 4026, pp. 480–497,2006.

[12] G. J. Pottie. Wireless sensor networks. *Proc. of Information Theory Workshop*, pp 139–140, 1998.

[13] Y. Shi and Y. T. Hou. Theoretical results on base station movement problem for sensor network. *Proc. IEEE INFOCOM'08*, pp. 376-384, 2008.

[14] Z. M. Wang, S. Basagni, E. Melachrinoudis, and C. Petrioli. Exploiting sink mobility for maximizing sensor networks lifetime. *Proc. HICSS*, IEEE, 2005.