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MOBILITY TO IMPROVE THE LIFETIME OF WIRELESS SENSOR NETWORKS: A THEORETICAL FRAMEWORK *

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Abstract Although commonly considered as a harm in wireless networks, mobility can potentially be beneficial to wireless sensor networks that usually consist of static nodes. A recent boom of applying mobile devices to improve the lifetime of wireless sensor networks has lead to a great deal of meaningful contributions, both in theory and practice. In this paper, we survey the efforts relevant to this topic. In addition, we also identify the lack of theoretical understanding of one of the approaches, namely *mobile sink*. We hence briefly describe a theoretical framework that we have obtained recently; it aims at bringing deeper insight on the optimal way of using mobile sinks for lifetime improvement.

Keywords: Wireless sensor networks, lifetime, mobility, mobile relay, mobile sink, mobile node, routing.

Introduction

Apart from their great advantages, *wireless sensor network*s (WSNs) are subject to many limitations, among which the energy constraint has become an increasing concern [1]. In WSNs, the size of a node should be sufficiently small to avoid altering phenomena of interest, and nodes, in many cases, should operate for a long period without human attendance. These requirements imply a capacity-limited and (possibly) non-renewable power source for each node. As a result, the

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longevity of WSNs under energy reserve limitations is a major problem that should be addressed before making use of such networks. To this end, many communication protocols for energy conservation in WSNs have been proposed. These include, among others, energy conserving routing (e.g., [2–5]), topology control (e.g., [6–9]) and clustering (e.g., [10–13]). Whereas these protocols focus on the **static** *sensor node*s, a recent trend indicates a focus shift to use of **mobile** elements (e.g., mobile *sink*s[1]) [14–22] to further improve the lifetime of WSNs.

In this paper, we first survey the topics that are related to applying mobile elements to improve the lifetime of WSNs. We categorize the approaches in using mobile elements into three classes: namely *mobile relay*, *mobile sink*, and *mobile node*. For each class, we describe the essence of related contributions and explain their pros and cons. Based on this literature survey, we also identify the lack of theoretical understanding of the mobile sink approach. As a consequence, we briefly investigate the problem of maximum lifetime data collection in WSNs by jointly considering sink mobility and routing. We build a unified framework to cover most of the joint sink mobility and routing strategies. Our investigation of the *maximizing network lifetime* (MNL) problem is based on a graph model. We show that the MNL problem involving multiple mobile sinks is NP-hard, but the MNL problem involving only a single mobile sink can be solved by an efficient approximation algorithm; we further generalize this algorithm to approximate the general MNL problem. Finally, we illustrate the benefit of using a mobile sink by applying our algorithm to numerical experiments.

The rest of this paper is organized as follows: Section 1.1 surveys related work. Section 1.2 states our assumptions and formulate the MNL problem. Section 1.3 proves the NP-hardness of MNL. Section 1.4 investigates in detail the sub-problem that involves only a single mobile sink. Section 1.5 reports the numerical experiment results on the algorithm we developed in Section 1.4. Finally, Section 1.6 concludes the paper.

1. Mobility to Improve Network Lifetime

There are two approaches for exploiting *sink mobility* to improve network lifetime; they depend on the relationship between the moving *speed* of a sink and the tolerable *delay* of the data delivery. On one hand, a sink can “transport” data with its movements if its speed is high enough to produce a tolerable data delivery delay [14–16], and hence spare nodes

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[1] These are the devices that collect data from WSNs; sometimes they are also termed *base station*s.

from the traffic forwarding load. On the other hand, moving the sink, even very infrequently, may still benefit the network lifetime, because it can lead to a global load balancing in the entire network [17–21]. The important fact is that the typical many-to-one traffic pattern in WSNs imposes on the nodes close to sinks a heavy forwarding load. While no energy conserving protocol alleviates such a load, moving sinks can distribute over time the role of bottleneck nodes and thus even out the load. Apart from sink mobility, allowing of a few *mobile node*s to substitute the heavily loaded static nodes can also benefit the lifetime [22].

1.1 Mobile Relay Approach

If a sink moves fast enough to deliver data with a tolerable delay, WSNs may take advantage of *mobility capacity* [23]. In this *mobile relay* approach [14–15], the mobile sink becomes a relay [23]; it "picks up" data from nodes (through one-hop transmissions) and transports the data with mechanical movements. This approach trades data delivery latency for the reduction of energy consumption of nodes. Shah et al. [14] investigate the case with unpredictable mobility. Since the hitting time of a relay to a node is not deterministic, their analysis focuses on the data success rate and required buffer size under random walks of the relays. Relying on predictable mobility, Chakrabarti et al. [15] are able to quantify the benefit of using mobile relays: the average energy consumption is 1/300 of static observer with single-hop communication and 1/3 of static observer with multi-hop communication. Kansal et al. [16] investigate the controllable mobility. Their proposal is a compromise between the mobile relay approach and the *mobile sink* approach (see Section 1.1.2): the sink relays data with its movements, and nodes transmit data (through a multi-hop routing if necessary) when the sink moves to the closest point to them. The focus of this effort is rather a system implementation than theoretical analysis; a field study is reported in [16].

1.2 Mobile Sink Approach

If a sink moves **infrequently**, its average speed is not high enough to produce tolerable data delivery delay. In fact, the sink mobility may take a **discrete** form: the movement trace consists of several *anchor point*s between which sinks move and at which they pause. Consequently, data packets have to be carried from their origin to the sinks through multi-hop routing. However, it has recently been observed that sink mobility still offers benefits in terms of network lifetime [17–18], thanks to a consequent load-balancing effect. Younis et al. [17] adopt a heuristic search to obtain sub-optimal sink locations; the sub-optimality brings only marginal improvement to the lifetime. Gandham et al. [18] present an *integer linear programming* (ILP) formulation. It is also not aiming at a global lifetime maximization; only local optimums are obtained for individual sink layouts. In a more recent contribution [19], Wang et al. make another formulation where the flows are pre-scheduled and the sink pause times become the variables of the lifetime optimization problem. However, a global lifetime maximization is still not achieved in these proposals because only a subset of possible flows is considered. Luo and Hubaux [20] take a continuum model and obtain some forms of asymptotic optimality by exploiting the symmetry of the assumed circular networks; it is difficult to apply these results to more general network topologies. Papadimitriou and Georgiadis [21] extend the formulation of [19] by jointly considering sink mobility and routing. The full scale problem is, however, not addressed because of its prohibitive complexity; the sink is confined to a limited number of positions in the numerical experiments. Note that, apart from [18], [17, 19, 20, 21] consider only a single mobile sink. Most importantly, the hardness of the joint sink mobility and routing for lifetime optimization is not evaluated in [17, 21]. Therefore, the lack of theoretical understanding of the optimality and tractability for mobile sink approach motivate us to come up with a new analytical framework.

On the practical side, although most proposals mentioned above come along with corresponding routing algorithms that work with mobile sinks, an implementation at code level has only appeared very recently [24]. By performing simulations with TOSSIM [25], Luo et al. [24] are able to quantify the side effects of sink mobility (e.g., higher routing overhead and packet loss) and justify the benefit of using mobile sinks.

1.3 Mobile Node Approach

Departing greatly from using mobile data collectors (either relay or sink), Wang, Srinivasan and Chua [22] presented a *mobile node*[2] approach to prolong network lifetime. The basic idea there is that a few powerful mobile nodes can be deployed to replace different (heavily loaded) static nodes. In their approach, a mobile node inherits the responsibilities of a static node with which it is co-located, such that the static node can shut down for energy saving. Whereas our framework will not cover this problem due to the fundamental difference between

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[2] The approach is termed“mobile relay” in [22], but we give it another name in order to be consistent with our terminology (where “mobile relay” is given to another approach [14–15]).

moving nodes and sinks, we note that this approach can achieve the same order of lifetime as the mobile sink approach only if a sufficient number of mobile nodes ($O(\sqrt{n})$ for an n-nodes network [22]) are deployed.

2. System Model and Problem Formulation

We model a WSN as a digraph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ where $\mathcal{V}$ represents $|\mathcal{V}| = n$ sensor nodes. There is a cost assignment c: $\mathcal{V} \times \mathcal{V} \to \mathbb{R}^+$, such that $\exists(i,j) \in \mathcal{E}$ if and only if the transmission energy (defined later) of $i \in \mathcal{V}$ is no less than $c(i,j)$. Apart from the sensor nodes, there is a set $\mathcal{S}$ ($|\mathcal{S}| = m < n$) of sinks that harvest data from the WSN. The following properties are specified for the network:

[a] Sensor nodes are stationary, but the sinks change their positions from time to time with a negligible travelling time between two positions.

[b] We only consider the case where the location of each sink coincides with the location of one of the nodes, such that the network topology (thus the graph $\mathcal{G}$) does not change with different locations of the sinks.

[c] Each sink inherits the data collection function of the co-located node. It behaves like a common node for receiving data, but it has long-range (wireless) communication facilities to transmit data out of the considered WSN.

[d] The data traffic flows from each node $i \in \mathcal{V}$ (i.e., all nodes are *source*s) to one of the *sink*s $s \in \mathcal{S}$ (through multi-hop relaying if no direct connection exists between i and s), and the control traffic involved, e.g., in a routing protocol, is not considered since it has the same effect to all nodes.

[e] Data transmission and reception are the dominating factors for the energy consumption of a node.

In addition, there are attributes associated with a node $i \in \mathcal{V}$:

[h] a value E_i (Joules) representing the initial energy reserve of the node,

[i] two values e_i^t and e^r representing the energies for the node to transmit and receive a unit of data (e.g., Joules/byte), and

[j] a rate λ_i of the information generation.

Fig. 1 shows the graph representation of a WSN.

We denote the lifetime by T and use t_k to indicate the time span for the kth *epoch*: a new epoch begins when some sinks change their locations. We also define p as a certain path and $f(p)$ is the flow that goes through p. Furthermore, P_{ik} stands for the set of paths between a node i and one of the sinks during the kth epoch and P_i^k represents the set of paths that go through node i in the kth epoch. Hence the problem

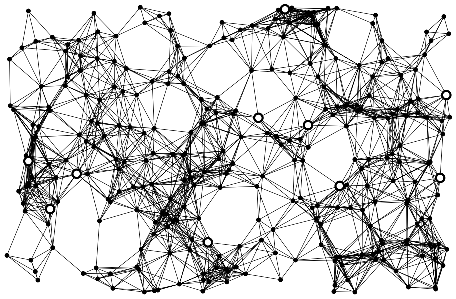

Figure 1. Network graph model. The WSN has 300 nodes (black points) and 10 sinks (white points). Nodes are uniformly distributed in a rectangular area. Here we take a cost assignment based on the Euclidean distance and a uniform transmission energy assignment.

of *maximizing network lifetime* (MNL) is formulated as follows:

$$\begin{aligned} \text{Maximize} \quad T = \textstyle\sum_k t_k & & & \quad (1)\\ \textstyle\sum_{p\in P_{ik}} f(p) - \lambda_i t_k &= 0 & \forall i,k & \quad (2)\\ \textstyle\sum_k \sum_{p\in P_i^k} f(p)(e_i^t + e^r) - E_i &\leq 0 & \forall i & \quad (3)\\ f(p),\ t_k &\geq 0 & \forall p,k & \quad (4) \end{aligned}$$

By defining $T = \sum_k t_k$, we implicitly assume the network lifetime as the time period for the first node to run out of its energy reserve [2].

3. Hardness of the Problem

The potential number of sink layouts for the MNL problem is $\binom{n}{m}$, which, by Stirling's approximation, is exponential in n for an arbitrary m. Given the exponential (in n) number of columns in the programming, it is not difficult to believe that the MNL problem is "very hard". In order to formally evaluate its hardness, we consider the following decision problem that is derived as a restricted case for the original MNL, which we term MSP (standing for Mobile Sink Positioning):

> INSTANCE: A graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, a cost assignment c, a set $\mathcal{S}$ of sinks with $|\mathcal{S}| < |\mathcal{V}|$, and for each $i \in \mathcal{V}$, a transmission energy e^t, an energy reserve E, a rate λ, and a positive real t.
>
> QUESTION: Does it exist a *sink layout schedule* $\{(sl_k, t_k)\}$ (sl_k is a vector of $[\delta_{is}^k]$ where $\delta_{is}^k : \mathcal{V} \rightarrow \{0,1\}$ and $\sum_i \sum_s \delta_{is}^k = |\mathcal{S}|$) such that the lifetime $T = \sum_k t_k$ is at least t?

THEOREM 1 *The MSP problem is NP-hard.*

We refer to [26] for detailed proof.

4. Maximizing Network Lifetime for a Single Mobile Sink (MNL-SMS)

The MNL-SMS problem is relevant because it is polynomially solvable in theory. In addition, we propose an approximation algorithm that solves the problem efficiently, which is then generalized to solve MNL along with other approximation algorithms.

4.1 Approximation Algorithm

The dual problem of (1–4) is given by:

$$\begin{aligned} &\text{Minimize} \quad {\textstyle\sum_i} E_i w(i) && && (5)\\ &{\textstyle\sum_i} \lambda_i W(i,k) &\geq\ & 1 \quad \forall k && (6)\\ &{\textstyle\sum_{j\in p,\ p\in P_{ik}}} w(j)(e^t_j + e^r) - W(i,k) &\geq\ & 0 \quad \forall i,k && (7)\\ &W(i,k),\ w(j) &\geq\ & 0 \quad \forall i,j,k && (8) \end{aligned}$$

where $W(i,k)$ is the weight assigned to a "commodity" (data flow injected at a node) from node i to the kth sink location and $w(j)$ is the weight assigned to a node j. The weight of a node $w(j)$ represents the marginal cost of using an additional unit of energy of the node, and the weight of a commodity $W(i,k)$ represents the marginal cost of rejecting a unit of demand of the commodity. Provided that the maximum lifetime is achieved, (6) says that the sum of λ_i multiplied by weights $W(i,k)$ for all n commodities in any epoch k is a least 1 (i.e., increasing the lifetime by one time unit without admitting yet another $\sum_i \lambda_i$ units of demand is not beneficial), and (7) states that the shortest path between an arbitrary node pair i and k (the cost of routing a unit of demand) is no less than $W(i,k)$ (the cost of rejecting a unit of demand from i to k); otherwise we could have a longer lifetime either by rejecting or by admitting (thus routing) more demands. Here the length of a path is computed as the sum (over all nodes along the path) of the product of node weight $w(i)$ and the node energy consumption $e^t_i + e^r$.

Our algorithm extends the one proposed by Garg and Könemann [27]. Let us denote the objective of the dual problem by $G(w) = \sum_i E_i w(i)$. In order to minimize $G(w)$, $w(i)$ should be as small as possible, but it is bounded from below by $W(i,k)$ through (6) and (7). Taking an arbitrary assignment w and $W(i,k) = \sum_{j\in\min\{p|p\in P_{ik}\}} w(j)(e^t_j + e^r)$ (i.e., the length of the shortest path from i to k), we meet (7). Then (6) becomes the following constraints:

$$\sum_i \lambda_i [\sum_{j\in p,\ p\in P_{ik}} w(j)(e^t_j + e^r)] \geq 1 \qquad \forall k$$

This assignment is not necessarily feasible because it might violate the above constraints. However, it can be made feasible by finding the most violated constraint and scale the assignment accordingly. In other words, if there is an *oracle* that identifies $\min_k \rho_k(w)$: $\rho_k(w) = \sum_i \lambda_i W(i,k) < 1$, we can scale all assignments $w(j), W(k,i)$, $\forall i, j, k$ by $[\min_k \rho_k(w)]^{-1}$ and make a feasible assignment. The oracle that computes $\min_k \rho_k(w)$ is simply an extension of the Floyd-Warshall algorithm [28] that computes all-pairs shortest path with a time complexity of $\Theta(n^3)$. Therefore, the dual problem is equivalent to finding a weight assignment w: $\mathcal{V} \rightarrow \mathbb{R}_0^+$ such that $G(w)/\rho(w):\ \rho(w) \equiv \min_k \rho_k(w)$ is minimized. We denote $\min_w[G(w)/\rho(w)]$ by β.

The approximation algorithm proceeds in iterations. Let w_{i-1}, W_{i-1} be the weight assignment at the beginning of the ith iteration and $\{t_{k,i-1}\}$ be the time schedule after iterations $1, \cdots, i-1$. In the ith iteration, we route $\sum_l \lambda_l$ units of commodity along the paths (and thus to the corresponding sink location) given by the oracle that computes $\min_k \rho_k(w)$ and let $t_{k,i} = t_{k,i-1} + 1$. Let $f_i(l)$ be the flow through node l and $p_{l,k}$, $\forall l$ be the paths suggested by $\min_k \rho_k(w)$ in this iteration. The new weight assignment to a node l is given by $w_i(l) = w_{i-1}(l)(1+\epsilon f_i(l)(e_l^t + e^r)/E_l)$, and the new weight assignments to a commodity are computed as $W_i(l,k) = \sum_{j \in p_{l,k}} w_i(j)(e_j^t + e^r)$. Note that $p_{l,k}$ is indeed the shortest path from l to k because it is suggested by the oracle that computes $\min_k \rho_k(w)$. Now the dual objective is updated as:

$$
\begin{aligned}
G(w_i) &= \textstyle\sum_l E_l w_i(l) \\
&= G(w_{i-1}) + \epsilon \textstyle\sum_l w_{i-1}(l) f_i(l)(e_l^t + e^r) \\
&= G(w_{i-1}) + \epsilon \cdot \rho(w_{i-1}) \qquad (9)
\end{aligned}
$$

Initially, the weight assignment to a node l is $w_0(l) = \delta/E_l$. The iteration stops when $G(w_i) \geq 1$ for the first time. The following theorem states the validity of this algorithm:

THEOREM 2 *Given* $\sum_i \lambda_i \leq E_l/(e_l^t + e^r), \forall l,$[3] *there is an algorithm that computes a* $(1-\epsilon)^{-2}$*-approximation to the MNL-SMS problem in time* $\Theta(n \log n) \cdot T_{\text{oracle}}$*, where* $T_{\text{oracle}} = \Theta(n^3)$ *is the time complexity for the oracle to compute* $\min_k \rho_k(w)$.

We refer to [26] for a detailed proof, as well as how to choose the parameters ϵ and δ.

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[3] This assumption is reasonable because each sensor node should be equipped with an energy source that is at least enough to forward data for all nodes in one time unit. Otherwise if a node l: $E_l/(e_l^t + e^r) < \sum_i \lambda_i$ is deployed close to a static sink (assuming a randomly deployed WSN), the network lifetime can be even less than one time unit. In addition, it can be proved that an approximation ratio of $(1-\epsilon)^{-3}$ is still achievable without this assumption.

Another significance of this algorithm is that, if we have an oracle that is able to solve the *p-median* problem (i.e., to compute $\min_k \rho_k(w)$ for multiple sinks):

> INSTANCE: A graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, a weight assignment $\omega\colon \mathcal{V} \to \mathbb{R}_0^+$, a length assignment $l\colon \mathcal{V} \to \mathbb{R}_0^+$, positive integer $K \leq |\mathcal{V}|$, and positive rational number B.
>
> QUESTION: Is there a set $\mathcal{P}$ of K "points on $\mathcal{G}$" such that if $d(v)$ is the length of the shortest path (i.e., the sum of all length assignments along the path) from v to the closest point in $\mathcal{P}$, then $\sum_{v\in\mathcal{V}} \omega(v) \cdot d(v) \leq B$?

then we are able to solve the original MNL problem. However, the p-median problem is NP-complete [29]. Yet, a reasoning procedure similar to what is shown in [30] suggests that if the oracle has an α-approximation, then the above algorithm provides an $\alpha \cdot (1-\epsilon)^{-2}$-approximation. In fact, Arya et al. [31] gave a $(3+\omega)$-approximation algorithm for the p-median problem. Therefore, we have an algorithm to approximate the original MNL problem with a factor of $(3+\omega)(1-\epsilon)^{-2}$.

5. Numerical Experiments

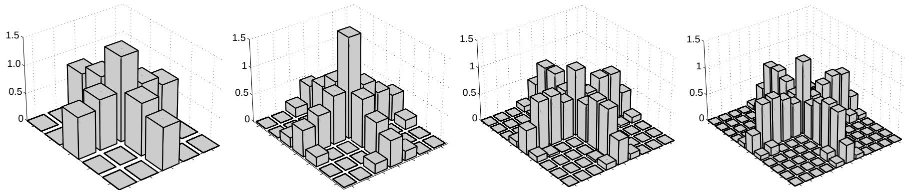
In this section, we test our approximation algorithm by positioning a single mobile sink in several WSNs of grid topologies (experiments on other topologies can be found in [26]). We always assign a homogeneous λ, e^t, and E to all nodes in order to facilitate the interpretation of the results. As a consequence, we can use $e = e^t + e^r$ to represent the energy spent by each node to forward one byte of data. Without loss of generality, we assume $\lambda = 1$, $e = 1$, and $E = |\mathcal{V}| = n$. We set $\epsilon = 0.01$.

For grid networks on $\sqrt{n} \times \sqrt{n}$ lattices, the maximum achievable lifetime by a static sink is $n/(\lceil (n-5)/4 \rceil + 1)$, because the lifetime is maximized if the forwarding load is balanced among the 4 neighbors of the sink. This lifetime can be obtained by putting the sink at the network center (if $\sqrt{n}$ is odd) or at any of the four nodes close to the center (if $\sqrt{n}$ is even). While this lifetime is converging to 4 when $n \to \infty$, the lifetime achieved by a mobile sink increases dramatically with the network size (Table 1). With an increasing network size, the number of alternative paths between an *s*-*t* pair is also increasing. Consequently, the load balancing effect becomes increasingly remarkable and thus produces significant improvements on the lifetime.

We illustrate the pause time in four networks in Fig. 2. Our observation is that the sink tends to move toward the periphery of a network with an increasing n. This observation also corroborates the result in [20]: the network periphery, as a sink moving trace, is asymptotically optimal.

$\lvert\mathcal{V}\rvert$	mobile sink	static sink (optimal)	improvement (%)
25	8.146	4.167	95.51
49	11.09	4.084	171.7
81	14.08	4.050	247.6
121	17.07	4.033	323.2

Table 1. Comparing the achievable lifetime between using a mobile sink and a static sink in grid networks.



(a) 25 nodes (b) 49 nodes (c) 81 nodes (c) 121 nodes

Figure 2. Pause times of a mobile sink in grid networks. The z-axis represents the pause time.

6. Conclusion

In this paper, we have first surveyed the approaches that apply mobile elements to improve the lifetime of WSNs, and we have also identified the lack of theoretical understanding of one approach called mobile sink. We have then presented a unified framework to analyze the *maximizing network lifetime* (MNL) problem in WSNs with mobile sinks. Our investigation, based on a graph model, jointly considers sink mobility and routing for lifetime maximization. We have formally proved the NP-hardness of the MNL involving multiple mobile sinks. We have also developed an efficient algorithm to solve the MNL problem involving only a single mobile sink; we have further generalized the algorithm to approximate the general MNL problem. Finally, we have illustrated the benefit of using a mobile sink through numerical experiments.

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