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Should I stay or should I go? Maximizing lifetime with relays

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ABSTRACT

As sensor mobility becomes more and more universal, Wireless Sensor Network (WSN) configurations that utilize such mobility will become the norm. We consider the problem of maximizing the lifetime of a wireless connection between a transmitter and a receiver using mobile relays. Initially, all relays are positioned arbitrarily on the line between the transmitter and the receiver and have arbitrary battery capacities. Energy is consumed in proportion to the distance traveled for mobility and in proportion to an exponential function of the distance over which information is sent for communication. Relays can move to different locations as long as they have the energy to do so. The objective is to find positions (which define transmission ranges) for the nodes that maximize the lifetime of the network. We study two models. The first is more restrictive, and corresponds to the case where relays are allowed to be set once at time zero (single deployment), while the second model corresponds to the case where relays can be adjusted multiple times (multiple deployments). We show how to compute an optimal solution for the case of no movement cost for both models. We consider a discrete version of the single deployment model, in which relays must be deployed on grid points. We provide two algorithms for this case: a dynamic programming algorithm and a binary search algorithm on potential lifetimes. We prove that both algorithms are FPTASs for the non-discrete problem, if batteries are not too small. We then show that if the initial positions of all relays are at either end of the transmission interval, then there exists a dominant order for the relays and the algorithms may be applied with this order to achieve an optimal solution in the discrete problem or an FPTAS for the non-discrete problem, if batteries are not too small. Based on these algorithms and on additional ideas we develop a number of heuristics for the multiple deployments model. We evaluate them using simulations and compare them with the lower bound of relays not moving at all and the upper bound of cost-free movement. Our simulations – across a range of mobility and transmission costs, sensible starting locations and battery capacities – demonstrate the benefit of moving over remaining at initial locations even for single deployment.

1. Introduction

Keeping the network alive for as long as possible is one of the main goals in any Wireless Sensor Network (WSN). This paper uses recent advances in node mobility (see El-Moukaddem et al. [1] and the references therein) to maximize the lifetime of a WSN using mobile-relay-based algorithms that move mobile relays to optimal locations along the line between a transmitter and a receiver.

Several papers address the problem of optimal placement of relays between a source and a destination to optimize other objective functions. Appuswamy et al. [2] optimize the capacity of the implied logical channel

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between the source and the destination under some interference model. This paper allows only grid placements of relays with the same, non-adjustable transmission range and does not consider movement cost.

Goldenberg et al. [3] prove that, for equal battery levels, the optimal locations for the relays on the line are equidistant apart and present an algorithm for moving nodes to their optimal locations using information from 1-hop neighbors only. They prove that their algorithm preserves the connections between all the relays.

Jiang et al. [4] develop a number of algorithms to speed up the rate of convergence and, hence, minimize the number of iterations required to move each of the nodes to their optimal locations. We extend the above works by taking into consideration the remaining battery life in each node and the effect that different mobility costs will have on the optimal locations of the nodes.

El-Moukaddem et al. [1] consider using mobile relays to enhance the lifetimes of existing network routes between static nodes in a 2D plane. Each relay can assist a single link between two nodes. They include realistic costs for movement and transmission and take into consideration the battery power remaining in each of the nodes.

In this paper we study the problem of maximizing the lifetime of a wireless connection between a stationary transmitter and a stationary receiver using mobile relays that are initially positioned arbitrarily on the line between the transmitter and the receiver and have arbitrary battery levels. For example, the relays may be initially located at the transmitter that deploys them to assist it with a transmission. We consider several variants of the problem depending on the deployment method. In many applications [3–5], relays are allowed to move only at time zero in order to decrease the amount of communication overhead between relays. It may also be the case that relays are initially deployed using an external agent, and cannot move by themselves. We refer to this model as the *single deployment* model. In the *multiple deployment* setting relays can move at any point in time.

Our contribution. We consider two network models, the first model corresponds to the case where relays are allowed to be set once, while the second model corresponds to the case where relays can be adjusted multiple times. In the first model relays can be deployed only at time 0 in an order preserving manner. The lifetime of the system is determined by the weakest link, namely by the lifetime of the relay whose battery is depleted first. This notion of *Lifetime of First Death* was consider by El-Moukaddem et al. [1]. We represent this problem as a non-linear program. The second model allows multiple deployments. Relays readjust their transmission ranges after a deployment. In this case we wish to maximize the length of time the transmitter can communicate with the receiver, that is the *Transmission Lifetime*.

We show how to compute relay locations for both models when there is no cost for movement. It turns out that for this case there exists a solution which is optimal with respect to both models, namely there exists an optimal single deployment order preserving strategy that maximizes both notions of lifetime.

For non-zero movement cost, we develop some structure for the optimal solution. In particular, we show that there is no justification for movement unless a relay dies, implying that a single deployment suffices when maximizing lifetime of first death. We also show that in any optimal solution the transmitter must be the last node to die.

We provide two algorithms which are optimal for the discrete problem (relays must be deployed on grid points) of maximizing the lifetime of first death. The first algorithm is a dynamic programming algorithm, while the second conducts a binary search on lifetimes for the optimum. For the case where the batteries are not too small, we show that both algorithms are FPTASs for the general problem, as their running times are polynomial in the size of the input and in $1/\varepsilon$ and their solutions are within a factor of $(1+\varepsilon)$ from the optimal for a given ϵ. It turns out that the dynamic programming algorithm has better worst-case running time on grid points, but the binary search algorithm can have better worst-case running time for the general problem. We then show that if all relays are initially located at the base stations (the endpoints of the transmission interval), then there is an ordering which is *dominant*, and thus we may solve the discrete version of this instance optimally and give an FPTAS if batteries are not too small by ordering with such an order and applying the dynamic programming or binary search algorithms. We note that this section is based on a section in [6] where sensors are initially placed at the endpoints and must cover the unit interval.

We experimentally test whether multiple deployments can assist in maximizing transmission lifetime. We find that just a single deployment is necessary in maximizing transmission lifetime. We develop heuristics for maximizing transmission lifetime based on this result and based on our theoretical findings and show that they are well-performing in simulation.

Related work. The numerous uses of mobility in WSNs are discussed in Francesco et al. [7] along with the challenges that arise when mobile nodes are introduced to a network such as maintaining connectivity. Along with mobile relays, other uses of mobility include mobile sinks and data MULEs.

Controlled sink mobility is considered by Basagni et al. [8], while predictable sink mobility is considered by Chakrabarti et al. [9], Chandra et al. [10] and Mhatre et al. [11]. Another approach considered in the literature is allowing the sink to move randomly as in Juang et al. [12] and Kim et al. [13].

Data MULEs were introduced by Shah et al. [14] and are further explored by Jain et al. [15].

Song et al. [16] build a prototype mobile node to demonstrate that mobile nodes are feasible. Kansal et al. [17] proposes using controlled mobility to optimize the power usage of a WSN and discusses a number of potential network features, for example tracks, that would make adding controlled mobility cost effective. Bar-Noy et al. [6] considered covering a line barrier with mobile sensors with either fixed or adjustable radii.

Paper organization. Formal descriptions of the problem, deployment methods, and network lifetimes are in given in Section 2. The case where movement is free of cost is analyzed in Section 3. Section 4 gives some structural results. Section 5 considers the discrete MaxFD. Section 6