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Discrete Optimization

Robust scheduling of wireless sensor networks for target tracking under uncertainty

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ABSTRACT

An object tracking sensor network (OTSN) is a wireless sensor network designed to track moving objects in its sensing area. It is made of static sensors deployed in a region for tracking moving targets. Usually, these sensors are equipped of a sensing unit and a non-rechargeable battery. The investigated mission involves a moving target with a known trajectory, such as a train on a railway or a plane in an airline route. In order to save energy, the target must be monitored by exactly one sensor at any time. In our context, the sensors may be not accessible during the mission and the target can be subject to earliness or tardiness. Therefore, our aim is to build a static schedule of sensing activities that resists to these perturbations. A pseudo-polynomial two-step algorithm is proposed. First, a discretization step processes the input data, and a mathematical formulation of the scheduling problem is proposed. Then, a dichotomy approach that solves a transportation problem at every iteration is introduced; the very last step is addressed by solving a linear program.

1. Introduction

1.1. Context

Since wireless sensors are becoming more and more affordable, more and more applications are now possible such as traffic control or battlefield surveillance (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Yick, Mukherjee, & Ghosal, 2008). Low-cost sensors are usually autonomous, equipped with a sensing unit and a battery. Their typical purpose is to track targets in their sensing range. They can be randomly deployed from an airplane or an helicopter in places lacking monitoring infrastructures. Sensors relying on technologies like drones and radars are suitable in military or humanitarian assistance contexts, where the infrastructures are destroyed or non-existent. In this paper, the investigated mission is to monitor a target with a known trajectory, such as a train on a railway, a vehicle on a road or a plane in an airline route. Since accessing sensors can be difficult in some environments, we may have no control on them during the mission. Then, in order to save battery lifetime, sensors can be switched off and waken up later. To minimize the energy consumption, the target is monitored by only one sensor at a time. Moreover, the target is subject to perturbations on its path, that may cause advances and delays. Consequently, our challenge is to find a *static* schedule of *sensing activities*, able to monitor the target at any time, without target loss despite perturbation. A *target loss* happens when the target is outside the range of any active sensor. A *sensing activity* is identified by a sensor, a starting date and a duration, to be computed offline, before the mission. During an *activity*, the corresponding sensor wakes up, collects information about the target for a certain amount of time, and then gets back to sleep status. Our aim is to find the most *robust* schedule, i.e. the one that resists to the largest possible earliness and tardiness.

1.2. Related work

There are plenty of WSN protocols for target tracking proposed in the literature, designed to achieve one or more goals. Usually, these protocols are dedicated to the optimization or management of different criteria. We present below a non-exhaustive list of the criteria addressed by those protocols:

- *Energy consumption*: this is one of the most critical aspects since the sensors generally have a non-rechargeable battery. For example, the framework designed in Zhang and Cao (2004) configures min-cost convoy trees using dynamic programming in order to save energy. Many protocols that focus on this aspect are based on LEACH (Handy, Haase, & Timmermann, 2002; Jindal & Gupta, 2013) or HEED (Younis & Fahmy, 2004).

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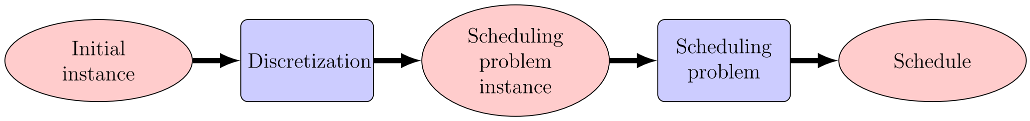

Fig. 1. Overview of the steps of the method.

- *Tracking precision*: can be achieved by selecting more sensors or by predicting the target location. A good precision technique can help deciding which sensors to wake up and make a better use of the energy. Yang and Sikdar (2003) and Xu, Winter, and Lee (2004) propose protocols based on prediction.
- *Scalability*: a WSN protocol should scale to different network sizes since a dense network can significantly increase the communication cost. Scalable protocols typically use cluster-based or distributed approaches instead of centralized ones. The authors in Kung and Vlah (2003) focus particularly on this aspect.
- *Fault tolerance*: target tracking may fail due to deficiencies or environmental events. This aspect has witnessed a growing interest recently (Jin, Ding, Hao, & Jin, 2014; Laoudias, Michaelides, & Panayiotou, 2014; Mannan & Rana, 2015; Oracevic & Ozdemir, 2014; Xie et al., 2012).

For a more exhaustive review on the criteria and the WSN protocols, the reader is referred to Naderan, Dehghan, Pedram, and Hakami (2012). A classification of target tracking algorithms from the security point of view is proposed in Oracevic and Ozdemir (2014). The problem investigated in this paper is related to track continuity. However, while WSN protocols generally assume that the target trajectory is random, our approach is based on a known trajectory. It could also be combined with a trajectory prediction method as in Xiao, Weirong, He, and Qin (2014), to be adapted to targets following a random trajectory, by periodically sending the prediction results as an input of our method. This procedure is also suggested by Demigha, Hidouci, and Ahmed (2013).

Only a few of these protocols are currently implemented using optimization techniques. The survey by Naderan et al. (2012) states that only one protocol, designed by Lee, Lin, and Wen (2006) and later extended by Yeong-Sung, Cheng-Ta, and Hsu (2010), is effectively using optimization techniques. This protocol configures an object tracking tree using a Lagrangian relaxation-based heuristic algorithm based on a 0/1 linear formulation. Their problem only handles communication mission and is frequency-based, i.e. frequencies of target movements from a sensor to another are supposed to be known.

In Atia, Veeravalli, and Fuemmeler (2011), the problem is to optimize the tradeoff between tracking performance and energy consumption. A scheduling problem is stated as a partially observable Markov decision process. The decision is to choose the set of sensors to activate at each time slot.

A distributed sensor activation algorithm DSA^2 that relies on binary sensors is designed in Chen, Cao, Li, and Sun (2009). The algorithm activates the sensors according to probabilities to detect targets. A robustness study is provided by changing parameters, such as the maximum velocity of the targets, the sensing range or the sensor density.

One of the most studied WSN problems in the field of optimization is the network lifetime maximization. Assuming that the targets are static, the aim is to select and schedule a sequence of subsets of sensors, in order to maximize the time during which all the targets are covered. Many variants of this problem have been investigated, such as MNLB (Maximizing Network Lifetime under Bandwidth constraints) and MCBB (Minimizing Coverage Breach under Bandwidth constraints), solved using heuristics (Wang, Thai, Li, Wang, & Wu, 2008) and further using column generation (Rossi, Singh, & Sevaux, 2011). Column generation is also a flagship technique to solve network lifetime maximization problems. Carrabs, Cerulli, D'Ambrosio, Gentili, and Raiconi (2015) handle heterogeneous networks and speed up the column generation using a genetic algorithm. Castaño, Bourreau, Velasco and Rossi (2015) take into account communication and multi-roles sensors. To solve the pricing problem, they propose two approaches: constraint programming and Branch-and-Cut based on Benders' decomposition. Singh and Rossi (2014) study some ways to schedule groups of active sensors after obtaining an optimal solution and propose a greedy heuristic and a genetic algorithm.

When the energy consumption of a sensor is variable, i.e. proportional to the number of monitored targets, the network lifetime maximization problem becomes polynomially solvable. Liu, Chu, Leung, Jia, and Wan (2011) provide a continuous linear formulation under this assumption.

In most of the research papers on WSNs, the notion of robustness is reduced to *survivability*, i.e. the ability to resist to unexpected failures such as enemy attacks or sensor deficiencies (Ellison, Fisher, Linger, Lipson, & Longstaff, 1997; Wang & Xiao, 2006; Wang, Lin, Chan, & Wang, 2013). This paper focuses on the ability of a sensor schedule to resist to target behavior perturbations, in order to reduce the risk of target loss. A prediction scheme proposed in (Pannetier, Dezert, & Sella, 2014) also aims at maintaining track continuity in ground battlefield surveillance, but supposes that the targets can move on and off a road.

Our previous study (Lersteau, Sevaux, & Rossi, 2014) proposes an exact approach to solve the minimization of energy consumption and the network lifetime maximization problems, whereas this paper addresses robustness issue of this problem.

For the sake of readability, the problem investigated in this paper is introduced step by step. Section 2 presents a preliminary step, called discretization, to transform the input data into a scheduling problem instance. Such a transformation is necessary to introduce the definition of stability radius, i.e. the measure of robustness, in Section 3. A diagram summarizes the different steps in Fig. 1. In Section 4, some upper bounds on the stability radius are provided. Sections 5 and 6 describe the proposed approach to solve the problem and the results of its implementation, respectively. Section 7 concludes the paper.

2. Preliminary concepts

2.1. Definitions

A set of *m sensors* $I = \{1, \ldots, m\}$ is randomly deployed in a two-dimensional region in order to monitor a single *moving target*. The positions of the sensors are known and static. Each sensor is able to monitor the target under its sensing range (disc of radius R). The action of monitoring is called a sensing *activity*. An activity consumes energy from sensor i, therefore the total activity duration cannot exceed its battery lifetime E_i, for all $i \in I$.

Without loss of generality, the planned target position is supposed to be exactly known at any time $t \in [0, H]$ where H is the monitoring horizon and defined by a continuous two-dimensional vector function $\mathcal{T}(t)$.

$$\mathcal{T} : t \mapsto (x, y) \text{ where } t \in [0, H],\ (x, y) \in \mathbb{R}^2$$

Table 1 describes the initial input data of the problem.

The goal of the problem is to find a robust schedule of sensing activities in order to avoid target loss. The requirements are the following: