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A hybrid exact approach for maximizing lifetime in sensor networks with complete and partial coverage constraints

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A B S T R A C T

In this paper we face the problem of maximizing the amount of time over which a set of target points, located in a given geographic region, can be monitored by means of a wireless sensor network. The problem is well known in the literature as Maximum Network Lifetime Problem (MLP). In the last few years the problem and a number of variants have been tackled with success by means of different resolution approaches, including exact approaches based on column generation techniques. In this work we propose an exact approach which combines a column generation approach with a genetic algorithm aimed at solving efficiently its separation problem. The genetic algorithm is specifically aimed at the Maximum Network α-Lifetime Problem (α-MLP), a variant of MLP in which a given fraction of targets is allowed to be left uncovered at all times; however, since α-MLP is a generalization of MLP, it can be used to solve the classical problem as well. The computational results, obtained on the benchmark instances, show that our approach overcomes the algorithms, available in the literature, to solve both MLP and α-MLP.

1. Introduction

Wireless Sensor Networks (WSNs) are usually composed of a large amount of sensing devices (*sensors*) scattered over a region of interest. Each sensor is generally capable of monitoring a certain portion of the space around itself (usually called its *sensing area*, and defined by the *sensing range* of the sensor). While each individual device has obvious limits in terms of range extension and battery lifetime, a coordinated use of multiple sensors together allow them to perform complex monitoring activities in possibly large areas, in fields as diverse as environmental control, military and healthcare applications, among others (see, for example, Alemdar and Ersoy, 2010; Pejanovic Durisic et al., 2012; Rawat et al., 2014).

Given the limited power of the batteries that usually keep sensing devices operational, an issue which has generated intense research interest in the last years is related to the optimization of battery consumption. In particular, the problem of appropriately use sensors to monitor a set of specific points of interests, known as *targets*, for as long as possible has been widely studied; the problem is usually known as Maximum Network Lifetime Problem (MLP). It has been mainly approached with methods aimed at finding several, possibly overlapping sets of sensors (defined *covers*) which can individually provide coverage for all the targets, as well as an activation time for each of them, such that the sum of the activation times of the covers in which each sensor appears is not greater than its battery life. The idea is then to activate the covers one by one, where by activating a cover we intend to turn on all the sensors which belong to it, while keeping all other sensors turned off.

In Cardei et al. (2005) the authors showed that MLP can bring improvements with respect to previous approaches in which sensors were divided into disjoint sets (that is, each sensor could only belong to a single cover). They also proved that the problem is NP-Complete, and proposed an approximation algorithm to solve it.

A column generation approach aimed at solving the MLP was proposed in Deschinkel (2011). In this work the author proposes a hybrid approach where the separation problem of the column generation technique is either solved heuristically or optimally by means of an appropriate ILP formulation. More details about this technique are given in Section 3. For a survey on hybrid algorithms, including the embedding of heuristics and metaheuristics into column generation frameworks, the reader may refer to Blum et al. (2008).

Several variants of MLP have been proposed as well, in order to adapt the problem to different contexts. Some of the proposed variants take into account cover connectivity (Alfieri et al., 2007;

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Castaño et al., 2015, 2014; Raiconi and Gentili, 2011; Zhao and Gurusamy, 2008), reliability issues (Cerulli et al., 2014), or consider sensors with adjustable sensing ranges (Cardei et al., 2006; Cerulli et al., 2012; Rossi et al., 2012). For many of these variants, efficient algorithms based on column generation have been proposed (Alfieri et al., 2007; Carrabs et al., 2015; Castaño et al., 2015, 2014; Cerulli et al., 2012, 2014; Raiconi and Gentili, 2011, Rossi et al., 2013).

Another interesting variant of the problem is the Maximum Network α-Lifetime Problem (α-MLP), which was proposed and studied in Gentili and Raiconi (2013). In this variant, a predefined portion of the overall number of the targets can be neglected in each cover. As will be better investigated in Section 2, α-MLP generalizes MLP and therefore each method aimed at solving this problem can also be used to face the original one. In Gentili and Raiconi (2013) the authors presented both a heuristic algorithm and an exact one, showing that large improvements in terms of the global network lifetime can generally be achieved by neglecting just a small percentage of targets in each cover. Furthermore, the authors also showed that such improvements can usually be mostly retained when some additional regularity conditions are taken into account, in order to guarantee a minimum global coverage level to each target.

In this work we propose a hybrid exact approach for the α-MLP problem, named GCG. While the overall structure of the algorithm is again based on the column generation technique, the main contribution of this work is the proposal of an appropriately designed genetic metaheuristic, which is used to solve its separation problem. As will be shown by discussing the results of our computational tests, the algorithm is proven to be highly efficient in terms of requested computational time, outperforming the algorithms presented in Deschinkel (2011) for MLP and Gentili and Raiconi (2013) for α-MLP.

The rest of the work is organized as follows. Section 2 formally introduces the problems and a mathematical formulation to describe them. Section 3 resumes the approaches presented in Deschinkel (2011) and Gentili and Raiconi (2013) to solve MLP and α-MLP. Section 4 describes our proposed genetic algorithm, while Section 5 presents the results of our computational experiments. Finally, Section 6 presents some final remarks.

2. Problems definition and mathematical formulation

Let $N=(T,S)$ be a wireless sensor network, with $T=\{t_1,\dots t_n\}$ being the set of the targets and $S=\{s_1,\dots,s_m\}$ being the set of the sensors. As previously introduced, each sensor is assumed to have a given sensing range, and to be powered by a battery that can keep it activated for a limited amount of time. In this work, we assume each sensor to be identical, therefore they all have sensing ranges of the same size and equal battery durations, normalized to 1 time unit. In Fig. 1(a) a sensor network with sensors $s_1,\dots,s_6$, targets $t_1,\dots,t_6$ and sensing ranges represented by circles is shown.

For each target $t_k \in T$ and sensor $s_i \in S$, let δ_{ki} be a binary parameter equal to 1 if t_k is positioned within the sensing range of s_i (it is *covered* by the sensor), 0 otherwise. For a subset of sensors $S' \subseteq S$ and a target $t_k \in T$, let $\Delta_{kS'}$ be another binary parameter equal to 1 if $\delta_{ki}=1$ for a given $s_i \in S'$, 0 otherwise.

Given a value $\alpha \in (0,1]$, we define $C \subseteq S$ to be a *feasible cover* (or simply a cover) for the network if its sensors cover at least $T_\alpha = \alpha \times n$ targets, that is, $\sum_{t_k \in T} \Delta_{kC} \geq T_\alpha$. Furthermore, we define a cover to be *non-redundant* if it does not contain another cover as a proper subset.

The Maximum Network α-Lifetime Problem (α-MLP) consists then in finding a collection of pairs (C_j, w_j) where each $C_j \subseteq S$ is a

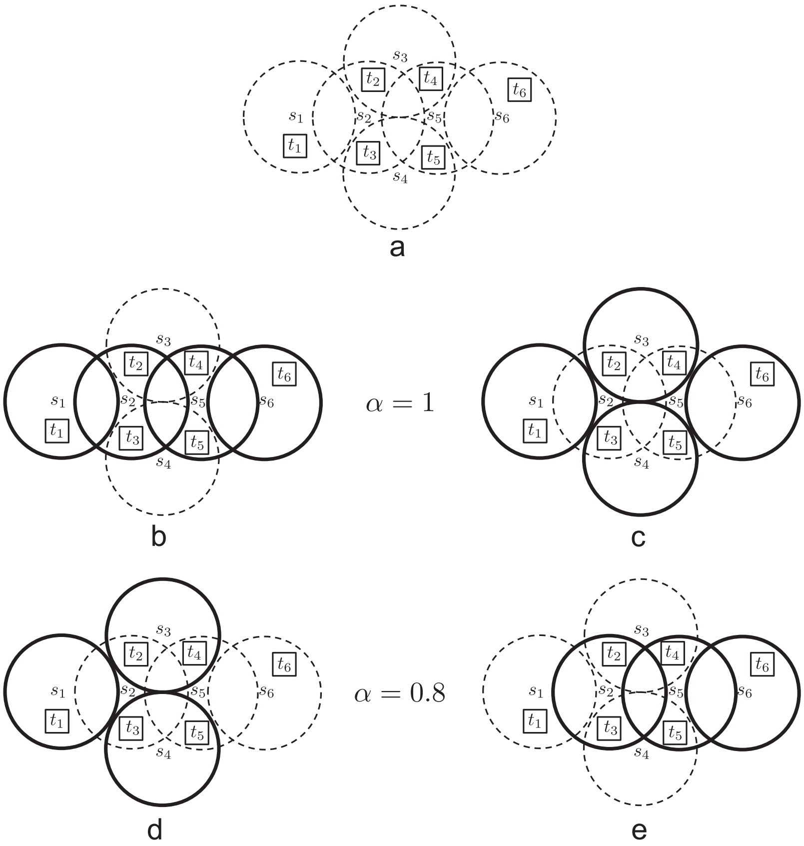

Fig. 1. Example network.