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Maximizing lifetime in wireless sensor networks with multiple sensor families

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ABSTRACT

Wireless sensor networks are generally composed of a large number of hardware devices of the same type, deployed over a region of interest in order to perform a monitoring activity on a set of target points. Nowadays, several different types of sensor devices exist, which are able to monitor different aspects of the region of interest (including sound, vibrations, proximity, chemical contaminants, among others) and may be deployed together in a heterogeneous network. In this work, we face the problem of maximizing the amount of time during which such a network can remain operational, while maintaining at all times a minimum coverage guarantee for all the different sensor types. Some global regularity conditions in order to guarantee a fair level of coverage for each sensor type to each target are also taken into account in a second variant of the proposed problem. For both problem variants we developed an exact approach, which is based on a column generation algorithm whose subproblem is either solved heuristically by means of a genetic algorithm or optimally by an appropriate ILP formulation. In our computational tests the proposed genetic algorithm is shown to be able to dramatically speed up the procedure, enabling the resolution of large-scale instances within reasonable computational times.

1. Introduction

Due to technological advances which enabled their deployment in relevant and diverse scenarios, wireless sensor networks (WSNs) have been studied extensively in the last years. Possible application contexts include environmental monitoring, traffic control, patient monitoring in healthcare and intrusion detection, among others (see, e.g., [1–3]). The general structure of a WSN is composed of several hardware devices (*sensors*) deployed over a given region of interest. Each sensor can collect information or measure physical quantities for a subregion of the space around it (its *sensing area*), or monitor specific points of interest in the area (*targets*). The targets inside the sensing area of a given sensor are defined as *covered* by it.

Individual sensors are usually powered by batteries which make it possible to keep them functional for a limited time interval, with obvious constraints related to cost and weight factors. Using a network of such devices in a dynamic and coordinated fashion makes it possible to overcome the limitations in terms of range extension and battery duration which characterize each individual sensor, enabling elaborate monitoring of large regions of interest. Prolonging the amount of time over which such monitoring activity can be carried out has therefore emerged as an issue of paramount relevance. This problem, generally known as maximum lifetime problem (MLP), has been widely approached in the literature by proposing methods to determine several possibly overlapping subsets of sensors which are independently able to provide coverage for the target points (*covers*), and by activating them one by one for appropriate amounts of time such that battery constraints are not violated. It should be noted that while sensors could be considered as belonging to different states during their usage in the intended application (such as receiving, transmitting, or idle) in this context two essential states can be identified. That is, each sensor may currently be active (i.e., used in the current cover, and consuming its battery) or not. Activating a cover refers therefore to switching all its sensors to the active state, while switching off all the other ones.

Many works have been proposed in the literature to address MLP and several problem variations. The problem was shown to be NP-Complete in [4]. Earlier works such as [4,5] presented approximation

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and heuristic algorithms to solve it. The proposed variants of the problem include, among others, cases where a certain percentage of targets may be left uncovered by each cover [6–8] or where the sensing ranges can be adjusted in order to provide optimal trade-offs among coverage and energy consumption [9–12]. In works such as [13–15] connectivity issues are taken into account in order to route the collected information to a central processing facility. In [16], the authors assume this data collecting node (which they call *sink*) to be able to move to different positions during the monitoring phase, and present two MLP variants; in the first one, the information collected by each node must be forwarded to the sink at all times, while in the second one, sensors may decide to locally store information to forward it to the sink when it moves to a more favorable location.

Moreover, while the sensing range of each device is typically only limited by a certain threshold distance (i.e., they provide coverage on 360° around them), some authors also investigated the case in which the sensing activity is limited to an adjustable restricted angle [17–19], as in the case of video cameras or ultrasonic sensors. Among the proposed resolution methods for MLP variants, column generation algorithms have recently proved to be effective methods to solve reasonably large instances to optimality [6,10–14,16,19].

Most of the above presented works take into account homogeneous networks, i.e., networks whose sensing devices are perfectly equal and therefore have the same capabilities. This assumption makes sense in many scenarios where a large number of devices based on the same hardware is deployed. However sensor heterogeneity in this contest has been studied as well, in terms of different metrics. In [20–24] a subset of sensors is provided with larger batteries, and in some cases has longer transmission ranges and better processing capabilities, often in relation to clustering schemes where such sensors serve as cluster heads (sometimes called supernodes). Other works consider heterogeneity in a non-hierarchical context, allowing individually different sensors. For example, sensors with possibly variable battery durations are discussed in [25,19], while heterogeneous sensing ranges were analyzed in [26,27].

Fewer research efforts have been devoted to the case of networks composed of distinct categories of sensors, each fulfilling a different purpose. Indeed, it could be of interest to monitor several aspects of the same region of interest. For example, while monitoring a certain geographical area for environmental control purposes, different types of sensors could be employed to monitor pollution levels, temperatures, vibrations, as well as for intrusion detection and other relevant properties. This interpretation of heterogeneity was discussed in [28], where the authors propose a hardware and software testbed for wireless sensor network applications, including sensors with auxiliary energy sources based on solar cells and modular sensor headers.

In this work, we study WSNs where sensors belong to different types, from now on defined as *families*, and present two variants of MLP, namely the maximum lifetime with multiple families problem (MLMFP) and the regular maximum lifetime with multiple families problem (MLMFP-R).

Note that, if each target needs to be covered by every family where the WSN is activated, then finding a solution would merely reduce to solving MLP separately for each family, with an objective function value equal to the minimum among such maximum lifetimes. In fact, the covers could be activated in parallel, and the monitoring activity would continue until one of the families has no covers available. However, such a hard requirement could be too restrictive for many real-world cases. It could be reasonable for a portion of the targets to be left uncovered by each family in each cover, as long as some minimum family-dependent threshold is met, and coverage of all the targets is provided by at least one of the families at all times. Consider, for instance, a fire detection scenario which makes use of different types of sensors to monitor heat, humidity and smoke levels. While perfect knowledge using all types of sensors for all target points would be ideal, detections with a high level of accuracy may still be possible if each target is covered by only one or two types of sensors, and the information gathered by sensors monitoring a subset of targets located in the same portion of the area suggests that a fire event is indeed happening. Some sensor types may be more relevant for the detection of the phenomenon of interest (e.g., heat or smoke); therefore, a balance between network lifetime and detection accuracy may be obtained by choosing a percentage of the targets that should be covered by such families at all times, which represents the above mentioned threshold.

The regular version of the problem (MLMFP-R) also takes into account some regularity constraints where the aim is to maximize the minimum amount of time for which each target is covered by each family in the solution.

For both problem variants, an exact approach based on column generation (CG) is developed and presented, as well as a genetic algorithm which is embedded within the CG to improve its performances.

The rest of the paper is organized as follows. In Section 2 we formally introduce the two problems. The column generation exact approach is described in Section 3. In Section 4 we present our genetic algorithm as well as its integration within the CG framework. Section 5 presents the results of our computational experiments. Finally, Section 6 contains our final remarks.

2. Notation and problems definition

Consider a wireless network (S,T,F), where $S=\{s_1,\dots,s_m\}$ is the set of the sensors, $T=\{t_1,\dots,t_n\}$ is the set of the targets, and $F=\{f_1,\dots,f_z\}$ is the set of the sensor families. As previously introduced, each sensor is assigned to a family and is able to monitor a subset of targets defined by its sensing range. For each $t_k \in T$ and $s_i \in S$, let γ_{ki} be a binary parameter equal to 1 if t_k is covered by s_i, 0 otherwise. Furthermore, let $\{S_1,\dots,S_z\}$ be a partition of S, such that $s_i \in S_a$ if the family of sensor s_i is f_a, $\forall a \in \{1,\dots,z\}$.

A cover $C_j \subseteq S$ is defined in the classical MLP problem as a subset of sensors such that each target of T is covered by at least one sensor in C_j, i.e., $\sum_{s_i \in C_j}\gamma_{ki} \ge 1 \ \forall t_k \in T$. For a cover to be feasible, we consider an additional condition which imposes a minimal coverage threshold to be satisfied by each family. That is, given the *coverage requirement* $0 \le \tau_a \le n_a$ associated with f_a, where n_a is the number of targets covered by the sensors in S_a, C_j is feasible if and only if the sensors in $C_j \cap S_a$ cover at least τ_a different targets.

The MLMFP problem consists of finding a set of feasible covers $C_1,\dots,C_u$ and of assigning a positive activation time $w_1,\dots,w_u$ with each of them, such that the overall network lifetime is maximized and the battery duration constraint for each sensor is not violated.

Let us assume that we can compute in advance the complete set of feasible covers $\mathcal{C}=\{C_1,\dots,C_\ell\}$. For each $s_i \in S$ and $C_j \in \mathcal{C}$, let ϕ_{ij} be a binary parameter equal to 1 if s_i belongs to C_j and 0 otherwise. Let us assume that each battery duration is normalized to 1 time unit. Then, MLMFP can be described by the following linear programming formulation:

$$[\mathbf{P}]\ \max \sum_{C_j \in \mathcal{C}} w_j \tag{1}$$

s.t.

$$\sum_{C_j \in \mathcal{C}} \phi_{ij} w_j \le 1 \quad \forall s_i \in S \tag{2}$$

$$w_j \ge 0 \quad \forall C_j \in \mathcal{C} \tag{3}$$