European Journal of Operational Research 241 (2015) 28–38

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Discrete Optimization

Exact approaches for lifetime maximization in connectivity constrained wireless multi-role sensor networks

Fabian Castaño [a,c,*], Eric Bourreau [b], Nubia Velasco [a], André Rossi [c], Marc Sevaux [c]

[a] Universidad de los Andes, Departamento de Ingeniería Industrial, Bogotá, Colombia
[b] Université Montpellier 2, LIRMM UMR 5506 – CNRS, Montpellier, France
[c] Université de Bretagne-Sud, Lab-STICC UMR 6285 – CNRS, Lorient, France

ARTICLE INFO

Article history:
Received 12 April 2014
Accepted 6 August 2014
Available online 17 August 2014

Keywords:
Integer programming
Wireless sensor networks
Column generation
Constraint programming
Benders' decomposition

ABSTRACT

In this paper, we consider the duty scheduling of sensor activities in wireless sensor networks to maximize the lifetime. We address full target coverage problems contemplating sensors used for sensing data and transmit it to the base station through multi-hop communication as well as sensors used only for communication purposes. Subsets of sensors (also called covers) are generated. Those covers are able to satisfy the coverage requirements as well as the connection to the base station. Thus, maximum lifetime can be obtained by identifying the optimal covers and allocate them an operation time. The problem is solved through a column generation approach decomposed in a master problem used to allocate the optimal time interval during which covers are used and in a pricing subproblem used to identify the covers leading to maximum lifetime. Additionally, Branch-and-Cut based on Benders' decomposition and constraint programming approaches are used to solve the pricing subproblem. The approach is tested on randomly generated instances. The computational results demonstrate the efficiency of the proposed approach to solve the maximum network lifetime problem in wireless sensor networks with up to 500 sensors.

1. Introduction

Wireless sensor networks (WSN) have undergone a growing popularity during the last decade (Arampatzis, Lygeros, & Manesis, 2005; Diamond & Ceruti, 2007; Hadjidj, Souil, Bouabdallah, Challal, & Owen, 2013; Othman & Shazali, 2012). The wide range of potential applications for sensors made them an interesting area of research (Yick, Mukherjee, & Ghosal, 2008; Zorbas & Douligeris, 2010). Data such as temperature, light, sound or pressure can be collected by sensors and then transmitted to the user through multi-hop communication. Military applications as depot monitoring or intrusion detections in remote environments, industrial applications as inventory control, environmental monitoring, health-care monitoring, among other fields are only a small sample of the fields into which WSN are used.

WSN are typically composed by a large amount of sensor nodes deployed to accomplish some monitoring and communications tasks. Sensors are constrained devices with low computing capabilities that are basically composed by three components (Anastasi, Conti, Di Francesco, & Passarella, 2009): a sensing subsystem, a processing subsystem and a wireless communication subsystem. These components are coupled to guarantee that each device is able to collect information from the environment, to decide how to manage that information and how and where to transmit that information to be processed. Additionally, the power supply is obtained from a battery provided with a limited amount of energy. As a consequence, energy usage is a major concern in wireless sensor network design. In most applications, the use of wireless sensors demands the efficient design of strategies to manage their energy while keeping network operating properly.

Some applications require the sensors to be located in remote or hostile environments in which sensor placement cannot be controlled. Instead, sensors are randomly deployed from a remote location and their operations cannot be planned before their deployment. Hence, the replacement of sensors batteries is not possible. Consequently, some scenarios require the operation of sensors to answer to unknown operating conditions and topologies. Then, the way in which sensors are used must be defined *in situ* after network topology is known.

This research considers target coverage with wireless sensor networks, *i.e.*, sensors are used to collect information from the targets located within their sensing range. In order to efficiently use

* Corresponding author at: Université de Bretagne-Sud, Lab-STICC UMR 6285 – CNRS, Lorient, France.
E-mail address: fabian.castano@univ-ubs.fr (F. Castaño).

http://dx.doi.org/10.1016/j.ejor.2014.08.013
0377-2217/© 2014 Elsevier B.V. All rights reserved.

sensors battery's energy, a typical approach is to deploy more sensors than actually needed. Then, it is possible to identify subsets of sensors (covers) able to satisfy the coverage (*i.e.*, the coverage of some or all the targets) and connectivity requirements (*i.e.*, the information must be transmitted to a base station) (Deschinkel, 2011; Raiconi & Gentili, 2011; Rossi, Singh, & Sevaux, 2012; Zorbas, Glynos, Kotzanikolaou, & Douligeris, 2010). Hence, lifetime, defined as the total time during which the WSN is able to provide target coverage and to send sensing information to the base station, is extended by activating these subsets at different moments. Therefore, such an approach can be successfully extended to consider WSN in which sensors can adopt different roles at different energy consumption rates.

A wide range of exact and heuristic approaches has been proposed to efficiently use the energy in wireless sensor networks. A complete review of approaches to efficiently use the energy on WSN is presented by Zorbas and Douligeris (2010). Efforts have been mostly focused on the design of methods to maximize network lifetime by using heuristic criteria (Deschinkel, 2011; Gentili & Raiconi, 2013) and hybrid approaches as linear programming based rounding methods (Cardei, Thai, Li, & Wu, 2005). Gu, Zhao, Ji, and Li (2011) demonstrate that the solutions for the sensors coverage and scheduling problem can be accurately represented by using pattern structures, where patterns (covers) represent the energy consumption rate of sensors during the time interval in which they are active. Exact approaches based on column generation (CG) are currently the state-of-the-art algorithms to solve coverage and scheduling problems in wireless sensor networks (Alfieri, Bianco, Brandimarte, & Chiasserini, 2007; Castaño, Rossi, Sevaux, & Velasco, 2013; Cerulli, De Donato, & Raiconi, 2012; Gu, Ji, & Zhao, 2009; Rossi et al., 2012; Singh, Rossi, & Sevaux, 2013). CG relies on covers and decomposes the problem in two subproblems. The restricted master problem (RMP) maximizes the network lifetime on a restricted set of covers, and the pricing subproblem (PS) generates new covers that may increase lifetime even further in the master problem.

CG has been shown to be efficient when simple network models are considered, however addressing the subproblem becomes very challenging when network models get more complex, *e.g.*, when connectivity is required or the adoption of different roles for sensors within the network is allowed. Hence, improvements to the classical exact methods are necessary in order to guarantee that optimal solutions are obtained.

Most research on maximum network lifetime in WSN is concerned with the design of strategies to efficiently use the energy considering a homogeneous set of sensors being either active or inactive (Cardei & Cardei, 2008; Cardei et al., 2005; Gentili & Raiconi, 2013; Lu, Wu, Cardei, & Li, 2005; Raiconi & Gentili, 2011; Slijepcevic & Potkonjak, 2002). An active sensor is able to monitor all the targets that are located within its sensing range and to establish communication with other sensors, or the base station, if they are located within its communication range. A sensor is *inactive* if it is neither monitoring nor transmitting and it operates at negligible energy consumption rate without performing any activity within the network. In this paper we adopt a more general approach to consider wireless sensors having up to three operation modes (Zhao & Gurusamy, 2008). An active sensor is a *source* if it is performing monitoring and transmission tasks and is a *relay* if it is only used to transmit the information collected by source nodes to other sensors or to the base station. We will show that both scenarios can be tackled in a similar way since the case considering only two operation modes is a special case of the one which considers three modes.

In order to solve the problem we propose an exact CG approach, where two methods are proposed for addressing the pricing subproblem. The first one used to address the pricing subproblem, also decomposes it into two, that are solved through a Branch-and-Cut approach based on Benders' decomposition. Additionally, it is reinforced by adding some valid inequalities and connectivity cuts that help to improve the performance of this approach. The second method used to address the pricing subproblem is based on constraint programming. It uses specialized graph variables with global constraints (tree constraint, global cardinality constraint and channeling constraints) to model an underlying pricing subproblem. A specialized constraint propagation scheme guided by specific problem information is used to bring results in a quasilinear number of decisions throughout the search process.

This paper is structured as follows. In Section 2 a detailed description of the maximum network lifetime problem with connectivity constraints is provided as well as the mathematical model adopted to tackle this problem. In Section 3, the solution approach based on CG adopted to solve the problem is presented. Section 4 introduces the two algorithms for addressing the pricing subproblem. In Section 5, the performances of these algorithms are measured, by incorporating them into the CG framework, and by solving the lifetime maximization problem on a large set of instances. Finally, conclusions and future work are presented in Section 6.

2. Problem description

Consider a set of sensors $\mathcal{S} = \{s_1, s_2, \dots, s_m\}$ randomly deployed to monitor a set of targets $\mathcal{K} = \{k_1, k_2, \dots, k_n\}$ and to transfer sensing information to the base station, denoted by s_0. Each sensor is able to assume three different roles within the network. A sensor is a *source* node if it collects information from the targets that are located within its sensing range R_s and transfer information to the base station or to other nodes located within its communication range R_c. In addition to its own collected data, a source may also transfer information sent by other sensors. A sensor is a *relay* node if it is not sensing and is used only to re-transmit information collected by source nodes to other sensors or to the base station. Finally, a sensor that is neither collecting nor transferring information is *inactive*. The complete list with the notation used along the paper is summarized in Appendix A.

Let $G(\mathcal{N}, \mathcal{A})$ be a directed graph where $\mathcal{N} = \mathcal{S} \cup \mathcal{K} \cup \{s_0\}$ is the set of nodes and $\mathcal{A}$ is the set of arcs used to indicate if communication is possible between sensor nodes or if a target is monitored by a given sensor. An arc $a(u, v) \in \mathcal{A}$, used to represent the possibility of transmitting information between the elements of the network, exists if: (*i*) $u \in \mathcal{K}$, $v \in \mathcal{S}$ and u is located within the sensing range R_s of v, (*ii*) $u, v \in \mathcal{S}$ and they are located within the communication range of each other or (*iii*) if the base station $v = s_0$ is located within the communication range of a sensor $u \in \mathcal{S}$.

The energy consumption rate (*i.e.*, the consumed power) of a sensor only depends upon its current role: the consumption rate of a source (respectively a relay and an inactive sensor) is denoted by E_s (respectively E_r and E_i). The set $\mathcal{E} = \{E_s, E_r, E_i\}$ contains the energy consumption rates of the sensors. In general $E_s > E_r > E_i$, but this hypothesis is not necessary here. If $E_s \leqslant E_r$, the relay mode is useless and can be discarded, consequently an active sensor is always a source. The latter case has been considered by Castaño, Rossi, Sevaux, and Velasco (2013), where the use of hybrid approaches is proposed to solve the problem.

Let P_j be a partition of $\mathcal{S}$ into three (non overlapping) sets: the source nodes (S_s^j), the relay nodes (S_r^j) and the inactive nodes (S_i^j). We define $\mathcal{N}_j$ as $\mathcal{N}_j = \mathcal{N} \setminus S_i^j$ and let $G[\mathcal{N}_j]$ denote the subgraph of G induced by $\mathcal{N}_j$. The partition P_j is said to be feasible if for all targets $k_i \in \mathcal{K}$, there exists a path from k_i to s_0 in $G[\mathcal{N}_j]$. Let Ω denote the set of all feasible partitions P_j, the maximum network lifetime problem with role allocation and connectivity constraints