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Wireless sensors deployment optimization using a constrained Pareto-based multi-objective evolutionary approach

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ABSTRACT

Sensors deployment is one of the most fundamental issues in wireless sensor networks (WSNs) design. One of the major challenges in sensors deployment is to find a tradeoff between conflicting objectives of network, coverage and lifetime, under certain connectivity constraints. This paper proposes a constrained Pareto-based multi-objective evolutionary approach (CPMEA) which aims at finding Pareto optimal layouts that maximize the coverage and minimize the sensors energy consumption for the sake of prolonging the network lifetime, while maintaining the full connectivity between each sensor node and the high energy communication node (HECN). In the proposed CPMEA, certain problem-specific operators are designed to direct the search into feasible regions of the search space. For this purpose, during the evolution, the designed operators are adapted to the objectives as well as constraints of the problem in order to make overall improvements on the CPMEA performance. In this paper, the proposed method is numerically examined in certain WSN test instances and a study of its performance is carried out using certain performance metrics. The results have shown the effectiveness of the designed operators as well as the superiority of the proposed approach over the non-dominated sorting genetic algorithm-II (NSGA-II).

1. Introduction

Advancements in wireless communication and micro-electro-mechanical systems (MEMSs) have caused an increased interest in the use of wireless sensor networks (WSNs) in numerous applications such as environmental monitoring and tracking, disaster management, security surveillance, improved healthcare and industrial diagnosis (Akyildiz et al., 2002; Juul et al., 2015; Nittel, 2009; Younis and Akkaya, 2008; Zhu et al., 2012).

Although remarkable advancements have been achieved in wireless sensor network technologies, the efficiency of these networks for collecting and transmitting data is still affected by sensors restrictions. Some of these limitations for a sensor may include sensing range, communication capability with other sensors, battery power, memory, and processing capability. In this regard, WSN deployment as one of the fundamental and major steps in WSN design is considered as a solution for diminishing the effects of sensors limitations (Nittel, 2009; Yick et al., 2008).

Optimal sensors deployment is the process of determining the locations of sensor nodes to simultaneously optimize some problem-specific desirable objectives that usually consists of 1) maximizing the covered area of the region of interest (ROI), and 2) minimizing the energy consumption of the WSN in order to prolong the network lifetime.

The coverage objective that relates to the issue of how well each point in the ROI is covered by the sensing range of sensors, can be considered as a measure of the quality of service (QoS) in a WSN, which is satisfied with a specific network design (Ghosh and Das, 2006; Meguerdichian et al., 2001). The other major issue in the design of WSNs is the limitation of sensor nodes energy resources. Reducing the energy consumption of sensor nodes leads the WSN to have a longer lifetime. Therefore, network lifetime is regarded as another main objective in a number of research (Liao et al., 2015; Mostafaei and Meybodi, 2013; Vieira et al., 2015).

Once the sensors are deployed in the ROI, they form a communication network based on their locations. Covering the ROI without considering the communications of the sensors will result in disconnected networks which seriously limit their use in real-world applications. Therefore, in WSNs, the connectivity between the sensor nodes and the high energy communication node (HECN), called sink, is as important as both coverage and lifetime (Poduri and Sukhatme, 2004).

It would be worth mentioning that coverage and connectivity are not unrelated problems and robustness of a WSN is directly

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related to them (Ghosh and Das, 2006). However, there exist certain researches and studies which focused only on the coverage and did not consider the connectivity during the WSN deployment, for example see Akbarzadeh et al. (2013), Argany et al. (2011) and Attea et al. (2012). Also, some studies simply assumed that the complete coverage will imply the connectivity in the network if the communication range of sensors is greater than (or equal to) twice their sensing range (Jia et al., 2009; Misra et al., 2011; Qu and Georgakopoulos, 2011; Zhang and Hou, 2005). However, depending on the sensors type (e.g. seismic, acoustic, chemical, and optical), the sensing and communication ranges of sensors may not satisfy the above-mentioned assumption to ensure the connectivity, e.g. see Jourdan and De Weck (2004a, b). Also, optimizing conflicting objectives such as coverage and lifetime may not lead to the complete coverage guaranteeing the connectivity via the above assumption.

Similarly, lifetime and connectivity are also related problems. Wireless communications in WSNs are considered as the main source of energy consumption in applications that the number of sensors is limited and the ROI is large (Ganesan et al., 2006; Li et al., 2006). In this regard, the energy storage capacity of the sensors prevents them from transmitting their gathered information directly to the sink, and hence, multi-hop communications, yielded by the connectivity issue, may be used to prolong the lifetime.

Accordingly, with respect to the considered objectives, the WSN deployment is inherently a multi-objective problem. Various formulations of this multi-objective problem is addressed as an NP-hard problem (Chaudhry et al., 2011; Konstantinidis et al., 2010; Wu et al., 2007; Younis and Akkaya, 2008). Multi-objective evolutionary algorithms (MOEAs) can be used for successfully solving such real-world NP-hard problems.

In the recent years, some MOEAs have been proposed to solve the WSN deployment but many of them did not specifically study the connectivity constraint during the optimization deployment and did not introduce problem-specific operators considering the connectivity constraint, see Jia et al. (2009), Jourdan and De Weck (2004a) and Konstantinidis et al. (2010). Nevertheless, there exist certain studies which converted the connectivity constraint into an objective and optimized it during the optimization of the other objectives, e.g. see Chaudhry et al. (2011) and Jameii et al. (2014). However, some scientists believe that treating constraints as objectives is not a good idea; and the constraints are required to convert infeasible solutions into feasible ones (Runarsson and Yao, 2005; Venkatraman and Yen, 2005; Wang et al., 2008). This paper proposes a constrained Pareto-based multi-objective evolutionary approach (CPMEA) in which some problem-specific operators are designed to direct the search into feasible regions of the search space. The aim of this approach is to find Pareto optimal layouts that maximize the coverage and lifetime simultaneously, while maintaining full connectivity between each sensor node and the sink. During the evolution, the proposed operators are adapted to the constraints and objectives of problem in order to improve the CPMEA performance.

The contributions of this paper include: (1) providing a flexible framework to address the deployment problem of WSNs, for which sensing devices are assumed relatively costly; (2) proposing an evolutionary approach that uses Pareto-dominance to optimize network coverage and lifetime as well as maintaining the network connectivity during the optimization process; and (3) presenting a problem-specific approach composed of a) a specific population initialization that produces the initial solutions in the feasible regions of the search space, b) specialized evolutionary operators for generating new high-quality feasible solutions at each iteration, and c) specific constraints that transform the infeasible solutions to feasible ones.

The rest of the paper is structured as follows: Section 2 illustrates the sensor deployment problem and its objective functions. Section 3 is devoted to the proposed constrained Pareto-based multi-objective evolutionary approach (CPMEA). The performance metrics are introduced by Section 4. Section 5 presents readers with experimental results and discussion. Finally, Section 6 ends the paper with conclusions.

2. The deployment problem

Wireless sensor networks (WSNs) are a collection of tiny battery-powered devices with sensing capabilities and limited onboard processing capabilities, storage, memory and short-range wireless communication links. Each sensor has a sensing range that is weakened gradually as the distance increases. Usually, a maximum sensing range for each sensor is defined and a binary sensing model is assumed. In the binary sensing model, a sensor is able to sense all the points inside its sensing range. Therefore, according to this model the sensing area of each sensor is assumed a circle with radius R_s.

Similar to the sensing range, a communication range of R_c is defined for each sensor. Two sensors are able to communicate with each other if the Euclidean distance between them is less than or equal to the minimum of their communication ranges. This kind of communication is called one-hop communication. As it was mentioned before, the energy storage capacity and the communication range of sensors do not allow them to transmit their gathered information directly to the sink in all the times. Therefore, sometimes gathered data are transmitted to the sink via multiple short hops, i.e. via multi-hop communication. It is worth mentioning that multiple short hops are more beneficial than a long hop in applications that the number of sensors is limited, the ROI is large and the sensors communication ranges are long (Konstantinidis et al., 2010).

Wireless sensors deployment problem is the process of determining the locations of sensor nodes forming a WSN. This process is done with respect to the sensors specific properties while it simultaneously optimizes certain specific objectives. In this Section, the problem is defined as a multi-objective problem, its objectives are also introduced and finally, it is mathematically formulized.

2.1. Problem definition

Consider a flat rectangular area A as ROI, k homogenous sensors with initial energy E, and a static sink H with unlimited energy. Also, assume without loss of generality that the sink is at the center of ROI for convenience. Wireless sensor nodes can sense all the points located within their sensing range R_s and also, they can communicate with other sensor nodes located within their communication range R_c. The sensors are responsible for monitoring the ROI and reporting the sensed data to the sink. Thus, each sensor node should be able to transmit its data to the sink directly or via multi-hop communication. The locations of sensors $\{s_i = (x_i, y_i)\}$ ($i = 1, 2, \ldots, k$) in the ROI are considered as decision variables of the WSN design which are to be optimized.

2.2. Constrained Pareto-based multi-objective optimization problem

As it was mentioned before, the WSN deployment problem is inherently a multi-objective optimization problem in which a tradeoff between conflicting objectives should be found. Moreover, the WSN deployment problem should consider certain constraints such as connectivity constraints during its optimization; hence,