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Ant colony optimization with greedy migration mechanism for node deployment in wireless sensor networks

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ABSTRACT

Node deployment is one of the most crucial issues in wireless sensor networks because it determines the deployment cost, the detection capability of the networks, and even the network lifetimes. To solve such a problem is an intricate task with realistic deployment factors such as deployment cost, connectivity guarantee, load balancing and channel collisions. In this paper, we consider the problem of grid-based coverage with low-cost and connectivity-guarantee (GCLC), and propose a novel deployment approach, ACO-Greedy, to settle this question. This approach is based on the ant colony optimization with greedy migration mechanism, which can quickly complete the full coverage, and markedly decrease the deployment cost. In addition, ACO-Greedy can dynamically adjust the sensing/communication radius to alleviate the energy hole problem and prolong the network lifetime. The simulation results reveal that our developed approach can not only decrease the deployment cost remarkably, but also effectively balance power consumption among sensor nodes and prolong the network lifetime in grid-based WSNs.

1. Introduction

Wireless sensor networks (WSNs) have gained worldwide attention in recent few years, particularly with the development in Micro-Electro-Mechanical Systems (MEMS) technology and wireless communication technology. A WSN consists of a large number of sensors, which have the ability of sensing, computing and communicating, observing and reacting to relative events and phenomena in a specific region (Akyildiz et al., 2002; Akkaya and Younis, 2005; Sohraby et al., 2007). WSNs can be employed in wide applications in both military and civilian scenarios, including environmental monitoring, security surveillance, health care, home entertainment, building control, traffic management, object tracking, etc. (Muhammad et al., 2011; Daniel and Luiz Affonso, 2010). Due to various advantages such as ease of deployment, extended transmission range, and self-organization, WSNs have been replacing the traditional networks (Chin-Ling and I-Hsien, 2010).

The design of WSNs is a complicated task which has substantial impact on the quality, efficiency and cost of various applications. The deployment issue is a fundamental problem for WSNs, in that it determines the performances of the networks, including the deployment cost, the detection capability, and the lifetime. As such node deployment has newly attracted the attention of the research community. As sensor nodes are equipped with low-energy batteries whose charge cannot be replaced after deployment, energy conservation is a major concern in WSNs, while the rate of energy depletion primarily relies on the nature of node deployment (Subir et al., 2011).

Generally, the main goal of node deployment is to realize coverage and connectivity. WSN coverage can be classified based on different applications or metrics. Generally, it falls into three types (Misra et al., 2011): (1) area coverage, such as (Tao et al., 2006; Cheng et al., 2007); (2) point coverage, such as (Ai and Abouzeid, 2006; Cai et al., 2007); and (3) barrier coverage, such as (Kumar et al., 2007; Ram et al., 2007). For point coverage, it is usually divided into two categories, i.e., continued-points-based coverage and grid-based coverage. In addition, network connectivity is indispensable for node deployment, because it determines the realizability of communication among the wireless sensor nodes, the node and base station, base station and the clients, the clients and the servers (Zhang and Liu, 2012).

In general, sensor nodes act as both data originator and data forwarder. Moreover, data transmission follows a many-to-one communication pattern. For this reason, sensor nodes close to the sink have larger energy consumption because they are burdened with heavier relay traffic. Sensor nodes in these areas tend to die early when they deplete their energy and result to what is called energy hole (Cheng and Ruzena, 2004). If this appears, no more data can be delivered to the sink, a considerable amount of energy is wasted, and the network lifetime ends prematurely (Wu et al., 2008; Rabun et al., 2011). Therefore, the energy hole problem

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should be taken into account for WSN designing, including node deployment.

In this paper, we consider and solve the problem of grid-based coverage with low-cost and connectivity-guarantee (GCLC). The objective of this problem is to design an algorithm which makes the needed region be covered by the deployed nodes. Besides, being defined by the total number of the deployed node in the network, the system cost is required as small as possible, as well as all the deployed nodes are connected through one or multiple hops. In this paper, a novel deployment approach, named ACO-Greedy, is proposed to solve the problem of GCLC. The goal of our approach is to avoid energy hole, decrease deployment cost, raise coverage speed, and finally better resolve the GCLC problem. ACO-Greedy is based on the ant colony optimization (ACO), but improves ACO by adding a new character, ants' greedy migration. ACO is a well-known intelligent algorithm where complex collective behavior emerges from the behavior of ants. AS one of the most successful swarm intelligence algorithms, it is very effective for solving NP-hard combinatorial optimization problems, such as traveling salesman problem (TSP) (Dorigo and Gambardella, 1997), and Quadratic Assignment Problem (QAP) (Gambardella et al., 1999). The problem of GCLC is also an applicable combinatorial optimization problem, thus ACO can be suitable for solving this problem.

The main contributions of our work are summarized as follows: (1) ACO is adopted and performed successfully for settling the GCLC problem in WSNs. (2) Based on non-uniform node distribution idea, we designed an non-uniform sensing/communication radius scheme, by which the energy hole problem is markedly alleviated and the network lifetime is distinctly prolonged. (3) By the high efficient scheme of object point selection in ACO, the heuristic value and the pheromone updating rule are reasonably defined, by which the total number of deployed sensors is decreased. (4) In ACO, it is the first time that the greedy migration scheme is proposed, thus it contributes to quickly completing the full coverage, as well as markedly decreasing the deployment cost.

The rest of the paper is organized as follows. In Section 2, literature review is elaborated. Section 3 presents the basic idea of our approach. The proposed novel algorithm is described in detail in Section 4. In Section 5, the performances of our approach are evaluated and analyzed by simulation results. Finally, the paper is concluded in Section 6.

2. Related work

Owing to various advantages, such as simplicity, flexibility, extendibility and implementability, the grid-based deployment has been widely used in WSNs to achieve significant improvements in terms of the network coverage and connectivity (Moro and Monti, 2011; Fadi and Hossam, 2013). Moreover, the grid deployment becomes necessary if sensor nodes are expensive and their operation is significantly affected by their positions. Hence, it has a broad range of applications, such as aircraft health monitoring, pollution flux monitoring, forest fire detection, and red wood trees monitoring (Fadi and Hossam, 2013). In the literature, the coverage of the grid-based WSNs has been extensively studied and several approaches have been designed to solve some experienced problems.

For grid-based coverage in WSNs, it has been proved to be NP-complete for deploying a network to k-cover points with minimum number of sensor nodes in Wei-Chieh et al. (2007). Moreover, it is also shown in Wei-Chieh et al. (2011) that the problem of deploying the minimum number of sensors on grid points to construct a WSN fully covering critical square grid cells is NP-complete.

An integer programming model has been developed to solve the sensor deployment problem of cost minimization under coverage constraints in Chakrabarty et al. (2002), then the framework of identifying codes is used to determine sensor placement for unique target location. A resource-bounded optimization framework has been presented for grid coverage in Dhillon and Chakrabarty (2003), and it is targeted at an average coverage as well as at maximizing the coverage of the most vulnerable grid points, but the storage and computing costs are too much on account of the large number of grid arrays.

Based on simulated annealing (SA) (Frank and Chiu, 2005), the grid-based node placement problem is formulated as a combinatorial optimization problem in WSNs, but the position of the sink and the connectivity problem have not been taken into account. Genetic algorithm (GA) has been used to determine optimal sensor placement for coverage (Habib, 2007; Yong and Xin, 2006). In Yong and Xin (2006), GA has been presented for grid-based node deployment, and a heuristic approach is presented to decode the chromosome, but the node communication problem has not been taken into consideration. ACO is also used for grid-based sensor deployment (Li et al., 2010), whose goal is to achieve full coverage with the minimal number of sensors, but it possesses large searching range, results in lots of inferior solutions and slow convergence. Besides, ACO with three classes of ant transitions is proposed in Liu (2012), where the coverage cost is obviously decreased compared with that in Li et al. (2010), while the deployment cost can be further improved. In addition, ACO based scheduling algorithm (Joon-Woo and Ju-Jang, 2012) and ACO with three types of pheromones (Joon-Woo et al., 2011) are proposed to solve the efficient-energy coverage problem in WSNs. However, the problem of energy hole has not been taken into account.

A virtual tree topology is constructed based on grid-based WSNs, and two node-placement methods, distance-based and density-based deployment schemes are proposed in Chih-Yung and Hsu-Ruey (2008) to balance the power consumption throughout the network, but this cannot achieve the deployment goal of the minimal number of sensor nodes. A multi-objective deployment method (Andreas et al., 2009) is presented for WSN deployment and power assignment, which is decomposed into a set of scalar sub-problems that are sorted according to their objective preference and tackled in parallel by using neighborhood information and evolutionary operators. The deployment issue in a planar grid region was formulated as a combinatorial optimization problem in Wu et al. (2007), where an approximate solution was proposed based on GA. The problem of sensors deployment was solved by devising the corresponding heuristic method. In He et al. (2010), an optimal deterministic deployment approach of sensor nodes is proposed by using the maximum multi-overlapping domains of target point s and the genetic algorithm. The genetic algorithm is used to find the least number of nodes to cover the target set and the optimal positions of these nodes from the candidate node positions. Literature (Guo et al., 2012) proposes a target coverage method based on grid scan. The best grid is chosen to place the next sensor. Meanwhile, a probabilistic sensing model is introduced, and the least sensing probability with which a node can sense a target is used to measure the whole coverage level. The deployment of indeterministic space with obstacles is researched in Zhang et al. (2010), where sensor's detection models and coverage quality evaluation are set up, and the watershed algorithm is employed to choose the deploying sub-area. However, there is no consideration for the energy hole problem among the above literature.

According to our survey, each of the above methods has certain limitations and the problem of GCLC in WSNs has not been completely solved by the mathematic optimization methodology. Our proposed algorithm, ACO-Greedy, and the other ACO-based