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Game theory based node scheduling as a distributed solution for coverage control in wireless sensor networks

Mahdi Movassagh, Hadi S. Aghdasi *

Computer Engineering Department, Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

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ABSTRACT

One of the important quality of services of Wireless Sensor Networks is the coverage, which focuses on providing near optimum coverage rate without decreasing network lifetime. Many distributed solutions have been proposed for this issue most of which try to select a minimum number of nodes as active while keeping others in sleep mode to preserve energy and extend network lifetime. However, these methods suffer from lacking a mathematical basis for their nodes selection approach. In this paper, we propose a distributed method for tackling this challenge by exploiting Game Theory as the mathematical basis for selecting active nodes named Game Theory based node Scheduling for Coverage control (GTSC). In GTSC, nodes compete each other to become active through exploiting their coverage redundancy, activation cost, the number of active neighbors, and uncovered region. The comparison of simulation results with the results of a well-known method and a state-of-the-art one shows that the proposed method outperforms both of them in terms of prolonging coverage, network lifetime, and energy efficiency, besides the redundancy rate reduction.

1. Introduction

For the last two decades, low cost and small size sensor nodes have attracted a lot of market and researchers' attention (Min et al., 2015; Wang et al., 2006). These devices usually are deployed in large numbers to form a network of cooperative nodes known as Wireless Sensor Networks (WSNs) (Assad et al., 2016). WSNs are used for wide range of applications, such as in agriculture, health care, industry, battlefield, and disaster management (Min et al., 2015; Wang et al., 2006; Wu and Cardei, 2016; Kisseleff et al., 2016; AlSkaif et al., 2015; Latif et al., 2016; Guo et al., 2015; Chen et al., 2016; Alkhatib, 2016; Li and Wu, 2016). In general, the basic idea is that each node collects regional information and sends them hop-by-hop to the sink. In most of the WSNs applications, it is infeasible to replenish the nodes' batteries. Thus, among WSNs constraints in memory, processing, and etc. energy constraint is the most important one. This makes new challenges for researchers to make customized or even new algorithms and methods for different tasks of WSNs like communication, processing, deployment, and so on (Hao et al., 2016).

In most of the mentioned applications, expected Quality of Services (QoSs) like maintaining coverage and connectivity besides the constrained battery capacity of nodes create challenges for researchers. One of the important challenges is the coverage and maintaining it at an acceptable rate while extending the network lifetime (Zhang and Hou, 2005). Knowing that usually nodes are deployed randomly and it is infeasible to replenishing their batteries, it is more acceptable to deploy nodes densely for satisfying mentioned applications (Shih et al., 2001). Thus, the challenge is to have a set of nodes be activated in each round — known as cover set — while keeping redundant nodes in sleep mode. Different solutions for this challenge can be put into two main categories: Centralized and Distributed (Zhu et al., 2012). In centralized solutions (Jameii et al., 2016, 2015) the general state of all nodes are gathered in the central station (sink) so that it selects cover set. In contrary, in the distributed methods, nodes decide their mode (active or sleep) according to their local information. Although centralized methods give the optimum result, they need to gather information from all the nodes in each round and send back the results to them, which are time and energy consuming processes. Thus, we have chosen the latter category in the rest of the paper to tackle the coverage problem.

Many distributed solutions have been proposed for solving the coverage problem in WSNs. Zhang and Hou have proposed the well-known optimal geographical density control (OGDC) method (Zhang and Hou, 2005) in which nodes autonomously schedule themselves based on local information but it suffers from a high degree of randomness in the method. Le et al. proposed CESS (Le and Jang, 2015)

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* Correspondence to: Computer Engineering Department, Faculty of Electrical and Computer Engineering, University of Tabriz, (51666-15813), Tabriz, Iran.
E-mail addresses: m.movassagh93@ms.tabrizu.ac.ir (M. Movassagh), aghdasi@tabrizu.ac.ir (H.S. Aghdasi).

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in which nodes schedule themselves cooperatively and based on the coverage contribution of their neighbors but besides problems with nodes' decision making it also uses poor coverage contribution detection mechanism. Ai et al. proposed a game theory based distributed method (Ai et al., 2007) to solve the problem by grouping nodes in cover sets which maximizes network lifetime while guaranteeing the expected coverage of the area. However, this method does not consider important parameters' calculation as a part of the method. Wang et al. proposed LDCC (Wang et al., 2009) in which nodes decide to go to off or on mode autonomously based on the hop counts to the Base Station (BS). While guaranteeing connectivity, this method can end in reduced coverage rate and increased number of blind points in the condition of low or medium density network or uncontrolled redundancy rate. Hefeeda and Ahmadi proposed PCP (Hefeeda and Ahmadi, 2007) which activates sensors to form virtual triangular lattices but cannot guarantee full coverage as a matter of random deployment.

In this paper, we aim to tackle coverage problem with a distributed method named Game Theory based node Scheduling for Coverage control (GTSC). In GTSC, nodes schedule themselves autonomously based on exchanging low-level local information of their neighbors with very low message passing cost. We expect that with low message passing we get better results comparing to state-of-the-art (CESS) method and well-known (OGDC) one due to using Game Theory as the mathematical logic of selecting initial nodes instead of random selection. In GTSC, nodes compete each other to become active through exploiting their coverage redundancy, activation cost, the number of active neighbors, and uncovered region. The simulation results show that the proposed method improves OGDC and CESS, up to 1.64 times in terms of network lifetime, 1.02 to 2.35 times in terms of coverage lifetime, 16% to 31% in terms of the number of active nodes, and 13% to 26% in terms of redundancy rate.

The rest of the paper is organized as follows. In Section 2 we give a short review of previous works for solving coverage problem in WSNs. Preliminaries and problem formulation are presented in Section 3. Section 4 is allocated for an explanation of proposed method. In Section 5, the simulation setup and results are presented. Finally, Section 6 concludes the paper.

2. Related works

Many distributed methods have been proposed in the field of WSNs coverage. Danratchadakorn and Pornavalai (2015) have developed CMSS in which the area is partitioned into cell grids and the main effort is to activate only one node in each cell. Each node exchanges information with its neighbors to establish neighbors' table, calculates cell-values for them and defines waiting times to decide its mode as sleep or active. Yang et al. (2015) have proposed a novel method for area coverage in which instead of a binary coverage (disk model) method, probabilistic coverage is used. Adulyasas et al. have used hexagonal shapes for investigating an optimum number of nodes to guarantee full connected coverage which ends in O-Sym method which optimizes the overlapping coverage of nodes to get efficient coverage (Adulyasas et al., 2015). Mamun et al. have proposed a method (Mamun, 2014) for node selection in which each node decides its mode based on the number of neighbors, residual energy, shared covering the area with neighbors, and selection repetition number. Byun et al. proposed a smart method (Byun and Yu, 2014) based on cellular automata using nodes' local interactions with its neighbors, called environmental state signaling, to help nodes decide their mode autonomously as active or inactive. Lu et al. after proving that optimum node scheduling is an NP-Hard problem (Lu et al., 2015), and giving a polynomial time constant factor approximation, have proposed MLCS scheme which uses Coverage and Data Collection Tree (CDCT) to schedule nodes in order to guarantee both coverage and connectivity.

A novel approach for distributed decision-making problems like in WSN problems is Game Theoretical approach. Game theory platform enables WSN researchers to look at nodes as real autonomous entities that compete (and may cooperate) for network resources (i.e. energy and/or bandwidth) (AlSkaif et al., 2015). For example, Karimi et al. have proposed a game theoretical approach (Karimi et al., 2014) for solving clustering problem. There are few methods using game theory for solving coverage problem (AlSkaif et al., 2015). Here we review some of them. Ai et al. have proposed a game theoretical approach called Distributed, Robust and Asynchronous Coverage (DRACo) method (Ai et al., 2007) in which each node decides to be in one of k cover sets based on its coverage metrics. They later extended their work (Ai et al., 2008). The main problem with Ai et al.'s two models (Ai et al., 2007, 2008) lies in the process of deciding the number of cover sets or k which is not a part of the proposed method while it has a deep effect on the results. He et al. proposed a game theory based method (He and Gui, 2009) that uses (Ai et al., 2008) to find maximum coverage set and then uses Minimum Layer Overlapping Subfields (MLOF) as nodes' utility function. The problem with this work has been considered its lack of scalability, which means the number of iterations for MLOF is not sub-linear to the number of sensor nodes.

Zhang et al. first finds and proves mathematically (Zhang and Hou, 2005) the optimal pattern of node deployment to guarantee both coverage and connectivity under the condition that communication range should be at least twice the size of sensing range. Then, they propose the well-known OGDC method in which each node schedules itself based on the local information and as close as possible to the optimum pattern. The advantage of OGDC is that it has the least possible message passing overhead and uses very simple calculations. However, the main problem with OGDC is the high degree of randomness. This is due to the fact that the initial node declaring itself as the active node triggers selection of other nodes. Thus, the optimality of whole the method depends on selecting an initial node(s) while it is selected randomly. This work is very close to our proposed method in principles but our proposed mathematical logic for node selection procedure outperforms OGDC.

A novel method called Coverage and Energy Strategy for WSN (CESS) (Le and Jang, 2015) is also studied to compare its efficiency with our proposed method. In this work Le et al. after setting up an energy consumption model for nodes, introduce a node scheduling method for both coverage and connectivity. In the initial round, each node finds its neighbors by exchanging coordinates. Then it decides to go to sleep mode if it is fully covered according to a special coverage contribution mathematical model. Then it sends sleep mode declaration message to neighbors. When it decides to go to sleep mode, it makes each neighbor rechecks its coverage contribution. In next rounds, each previously active node decides its mode according to its energy level: (1) it remains active if its energy level is normal, (2) but if its energy level is low (below threshold), it sends HELP message and waits for volunteering neighbors. If it is fully covered by its volunteering neighbors, it sends back a list of to be activated nodes from the list of volunteered neighbors. (3) If its energy level is critical, it sends DUTY message, which turns neighbor nodes' mode to initial one. The first problem with this method is with its model for calculating coverage contribution. The mathematical model used for this purpose does not give the rate of coverage and just shows if the node is redundant or not and even for this goal it is an approximate model and does not give an exact answer (Tezcan and Wang, 2007). Besides, the main problem with this method is that it gives the duty of selecting active nodes to the low energy nodes. While this procedure is another selection problem and has NP-complete difficulty, the authors do not suggest a method for solving this issue. We will show that this issue makes big problems for CESS.

3. Preliminaries and problem formulation

3.1. Parameter description

Here we discuss three parameters used in our formulas and their theoretical and practical features.