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A new maximum fault-tolerance barrier-coverage problem in hybrid sensor network and its polynomial time exact algorithm

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ABSTRACT

This paper introduces a new maximum fault-tolerance barrier-coverage problem in hybrid sensor network, which consists of a number of both static ground sensors and fully-controllable mobile sensors. The problem aims to relocate the mobile sensor nodes so that the fault-tolerance of the barrier-coverage of the hybrid sensor network is maximized. The main contribution of this paper is the polynomial time exact algorithm for this new problem.

1. Introduction

A wireless sensor node refers a microelectronic device which consists of a central processing unit, a wireless (usually radio) transceiver, a power source such as a battery, and most importantly one or more sensing units to observe designated events around it. Wireless sensor network consists of a number of low-cost wireless sensor nodes and is convenient to deploy for a wide range of application scenarios. Initially, wireless sensor network has been investigated for military applications. Recently, this innovative technology is also being adopted to construct various civilian monitoring and surveillance applications with reasonable cost [2,4,6].

1.1. Full-coverage, partial-coverage, and barrier-coverage models

In the literature, the term *coverage* of a wireless sensor network refers the quality of surveillance service that the sensor network can offer. Based on the requirement, the coverage provided by wireless sensor network can be largely categorized into two categories. In detail, to provide *full-coverage* over an area of interest, a wireless sensor network should be able to monitor the entire area of interest concurrently [5,7–10,23,28]. On the other hand, *partial-coverage* can be provided by a wireless sensor network if the network does not meet the requirements to provide full-coverage but satisfies a certain requirement [11–14]. *Barrier-coverage* is a partial-coverage model, which can be offered by a wireless sensor network over an area of interest if any intruder of interest who trespasses into the area from outside is guaranteed to be detected by the sensor network [15–18] (see Fig 1). Due to its important applications such as enemy intrusion detection in the battlefield, barrier-coverage has received lots of attention recently.

1.2. Fault-tolerance concept in full-coverage and barrier-coverage models

In many deployment scenarios, a number of static wireless sensor nodes are randomly deployed over an area of interest and thus the sensor network has sufficient degree of coverage redundancy. Over years, many efforts are made to exploit the redundancy to improve the fault-tolerance as well as the lifetime of the coverage in the sensor network of cheap static ground sensors.

Within an area of interest covered by a wireless sensor network providing full-coverage with high redundancy, any target of

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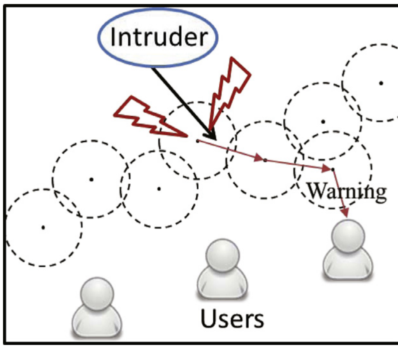

Fig. 1. A wireless sensor network offers barrier-coverage over an area of interest if it can detect any designated trespasser who enters the area.

interest within the area is likely to be observed by more than one sensor node at the same time. Specifically, by having the sensors in a way that every subregion in the area of interest is being observed by at least k sensors at the same time for some positive integer k, the full-coverage of the sensor network can provide up to any $k-1$ node failures. Naturally, by showing that a wireless sensor network has larger k, we can claim that the full-coverage of the sensor network has higher fault-tolerance against node failure. In the literature, one can show that the full-coverage of a wireless sensor network can endure up to k node failures by computing k node-disjoint subsets of the sensors such that each subset has enough sensors to monitor whole area of interest. In theory, the problem of computing maximum number of such subsets is known to be NP-hard and a number of approximation algorithms are introduced.

On the other hand, the goal of barrier-coverage is to monitor any intruder who trespasses into the area being surrounded by a sensor network. Therefore, to show that the barrier-coverage provided by a sensor network can endure up to k node failures, it is necessary to compute k node-disjoint subsets such that each subset can provide the desired barrier-coverage. Previously, Kumar et al. showed that the problem of computing the maximum number of node-disjoint sensor subsets can be modeled as the problem of computing the maximum number of node-disjoint paths in a graph induced by the sensor network and showed that the problem is polynomial time solvable [17].

1.3. Contributions and outline of this paper

Thanks to the recent advances, various kind of mobile sensor nodes such as flying drones have been introduced. Motivated by such development, there have been a branch of researches which exploit mobile sensor nodes for surveillance or intrusion detection in the context of hybrid sensor networks, which consist of a few mobile sensor nodes and a number of traditional (cheap and ground) sensor nodes [1,19–22]. Since the cost of mobile sensor nodes are expected to be very high compared to the cost of the traditional sensor nodes, the main role of the mobile nodes tend to assist ground sensor nodes and reinforce their surveillance capability rather than constructing their own (mobile sensor nodes only) sensor network for surveillance.

Main contributions. This paper introduces a new optimization problem in hybrid wireless sensor network of both mobile and static sensors whose goal is to maximize the fault-tolerance of barrier coverage provided by the sensor network. We formally define this problem as the *maximum fault-tolerance barrier-coverage problem in hybrid sensor network (MFBP-HSN)*. Compare to the existing maximum fault-tolerance barrier coverage problem in (static) wireless sensor network, our problem requires to determine how to relocate the available mobile sensor nodes and to compute the maximum number of (static and mobile) node-disjoint paths at the same time. Apparently, this is a difficult to problem as each mobile node can be positioned at any place on 2-dimensional Euclidean space and therefore the feasible solution space is infinite. To deal with the complexity, we first propose a new graph conversion technique to induce a new abstract graph from the original hybrid sensor network. Then, we use this graph as an input of our algorithm for MFBP-HSN. Most importantly, we show that this algorithm produces an optimal solution for MFBP-HSN and its running time is polynomial.

Outline of the paper. The rest of this paper is organized as follows. Section 2 presents the related work and Section 4 provides some preliminaries. In Section 3, we introduce the formal definition of MFBP-HSN. Section 5 includes our main result, which is the polynomial time exact algorithm for the MFBP-HSN. Finally, we conclude this paper in Section 6.

2. Related work

When it comes to the full-coverage of wireless sensor networks with static ground sensor nodes, the maximum fault-tolerance coverage problem is similar to the maximum lifetime coverage problem. This is because that one popular approach to maximize the lifetime of full-coverage of wireless sensor network of ground sensors is (a) computing the maximum number node-disjoint subsets such that each subset can full-cover the whole area of interest and (b) activating each subset one by one (activity one subset while the others are in a sleep mode until the nodes in the currently activated subset are exhausted) so that the total time period that the area of interest is maximized. Apparently, by activating multiple node-disjoint subsets at the same time, we can obtain higher level of fault-tolerance in full-coverage.

A sensor network is said to provide barrier-coverage over an area of interest if any trespasser which moves into the area is guaranteed to be detected by the sensor network. The barrier-coverage model is different from the traditional full-coverage model since it does not require to monitor the whole area of interest concurrently. As barrier-coverage model needs less number of nodes and is still effective to monitor any intruder, it is a very important concept for several main applications of wireless sensor networks such as intrusion detection. Originally, the concept of barrier-coverage has been introduced by Gage [24] in the context of robotic sensors. In [15], Kumar et al. introduced the concept of k-barrier-coverage. A sensor network provides k-barrier-coverage over an area of interest when an intruder moves into an area of interest, at least k sensors should be able to detect this. This means that k-barrier-coverage offers fault-tolerance against up to $k-1$ node failure. Since then, a considerable amount of attention has given to this model.

A k-barrier-coverage can be achieved by activating k node-disjoint subsets at the same time. In [15], Kumar et al. has modeled this as the problem of computing maximum number of node-disjoint paths in a graph which is induced from a given wireless sensor network of static nodes. This is a significant result because this problem of computing maximum number of node-disjoint paths in a graph is polynomial time solvable while the problem of maximum number of node-disjoint subsets such that each subset can fully cover the area of interest remains NP-hard. A distributed algorithm for this problem is introduced by Ban et al. [25]. Recently, Kim et al. [26] has shown that a particular type of attack can be launched by intruder if the consecutive operation schedule of barriers is not carefully designed.

As micro-electronic technologies have advances, a number of mobile sensor nodes such as drone flights are introduced. Since it is expected that the cost of mobile sensor nodes are significantly higher than the traditional ground sensor nodes, the main