Computer Networks 53 (2009) 2458–2475

Contents lists available at ScienceDirect

Computer Networks

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

Two and three-dimensional intrusion object detection under randomized scheduling algorithms in sensor networks

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ARTICLE INFO

Article history:
Received 18 June 2008
Received in revised form 30 April 2009
Accepted 3 May 2009
Available online 19 May 2009

Responsible Editor: J. Lopez

Keywords:
Wireless sensor network
Randomized scheduling algorithm
Coverage
Intrusion object
Energy consumption
Two-dimensional
Three-dimensional

ABSTRACT

We are interested in wireless sensor networks which are used to detect intrusion objects such as enemy tanks, cars, submarines, etc. Since sensor nodes have a limited energy supply, sensor networks are configured to put some sensor nodes in sleep mode to save energy. This is a special case of a randomized scheduling algorithm. Ignored by many studies, an intrusion object's size and shape are important factors that greatly affect the performance of sensor networks. For example, an extremely large object in a small sensor field can easily be detected by even one sensor node, no matter where the sensor node is deployed. The larger an intrusion object is, the fewer sensor nodes that are required for detection. Furthermore, using fewer sensor nodes can save resources and reduce the waste of dead sensor nodes in the environment. Therefore, studying coverage based on intrusion object's size is important. In this paper, we study the performance of the randomized scheduling algorithm via both analysis and simulation in terms of intrusion coverage intensity. In particular, we study cases where intrusion objects occupy areas in a two-dimensional plane and where intrusion objects occupy areas in a three-dimensional space, respectively. We also study the deployment of sensor nodes when intrusion objects are of different sizes and shapes. First, sensor nodes are deployed in a two-dimensional plane and a three-dimensional space with uniform distributions. Then, they are deployed in a two-dimensional plane and a three-dimensional space in two-dimensional and three-dimensional Gaussian distributions, respectively. Therefore, our study not only demonstrates the impact of the size and shape of intrusion objects on the performance of sensor networks, but also provides a guideline on how to configure sensor networks to meet a certain detecting capability in more realistic situations.

1. Introduction

Wireless sensor networks (WSNs) have become an important technology, combining sensing technology, embedded computing, distributed information processing, and wireless communication technology [25,26,38–74]. WSNs have broad applications [6,27], such as medical monitoring, environment pollution monitoring, forest fire monitoring, target tracking, combat field reconnaissance, and military command and control, and so on. Data collection is the basic objective of in these applications. Data collection capability of a sensor network depends on its sensing coverage and network connectivity. Sensor nodes are often powered by batteries, and it is often difficult or

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doi:10.1016/j.comnet.2009.05.002

impossible to recharge the deployed nodes. Great efforts [1,2,7,8,10–12] have been devoted to minimizing the energy consumption and extending the lifetime of the network.

Although energy efficiency is the essential requirement for WSNs, it should not be achieved at the cost of reducing network coverage, which is usually a major Quality of Service (QoS) metric of WSNs [23]. As sensor nodes are usually densely deployed, they are often highly spatially-redundant [20]. Therefore, energy efficiency and high sensing coverage can be achieved simultaneously by exploiting the spatial redundancy among sensor nodes. Many research efforts have been devoted to sensor scheduling algorithms that turn off redundant sensor nodes for energy saving [1–5,7,14,17].

Since maintaining location information and time synchronization introduces extra energy and computational overhead, some scheduling schemes [1,7,9,13,19] do not require location information or precise time synchronization of sensor nodes. In [16], the authors proposed several sensing scheduling protocols and analyze the performance of object detection and network lifetime. The joint problem of coverage and connectivity were considered recently in [9,15,18,22]. In [18], the authors considered a network with sensor nodes deployed strictly in grids. The joint problem in more general sensor networks where the sensor nodes are deployed at random was investigated in [9,22]. Similar work was done in [21], in which the authors also present a Coverage Configuration Protocol (CCP) that can provide fully coverage of a convex region. In [9–11,24], the authors have studied a k-set randomized scheduling algorithm where sensor nodes are randomly divided into k disjoint subsets (S_j; $j = 1,2,\ldots,k$) that work alternatively. In other words, at any time, only one set of sensor nodes are working, and the rest of the sensor nodes sleep.

Many studies only consider cases where intrusion objects are modeled as a point on a two-dimensional plane. In reality, an intrusion object is far larger than a point. In a sensor network deployed to detect enemy tanks or to detect people crossing a country's boundary, intrusion objects' sizes are totally different. A tank's size could be larger than the sum of the sensing range of several sensor nodes. We observed that the larger an intrusion object, the more likely it is that the intrusion object will be detected, and the fewer sensor nodes are required.

Furthermore, sensor nodes and intrusion objects are not necessarily on a two-dimensional plane, and the shapes of the intrusion objects often span intro three-dimensional space. For example, in an underwater sensor network, sensor nodes may be deployed in different depths to detect enemy submarines or other underwater intrusion robots. Another example is warehouse monitoring, in which sensor nodes are deployed on shelves to monitor goods in a warehouse. The sensing area is in fact three-dimensional, and the monitored area and objects always occupy a three-dimensional space. The size and shape of an intrusion object have impacts on the sensing capability of sensor networks. Therefore, in many applications, three-dimensional considerations are more realistic. Meanwhile, the sensing area of a sensor node should be also considered to be a three-dimensional space.

In this paper, we first study the intrusion coverage intensity via both analysis and simulation when the intrusion object occupies an area in a two-dimensional plane. The intrusion coverage intensity is defined as the probability that a given area at a given time is detected by at least one active sensor node. Furthermore, we study the intrusion coverage intensity of intrusion objects occupying a three-dimensional space, and the sensing fields of sensor nodes are expressed as spheres. To further approach reality, we study the case when sensor nodes are deployed using non-uniform distributions. In these scenarios, we study how the sizes and shapes of the intrusion objects influence the sensor network's configuration. Thus, through the study, we provide a guideline on the number of sensor nodes needed to meet certain levels of intrusion coverage intensity in more realistic settings.

The rest of the paper is organized as follows. We introduce related work on object detection in sensor networks in Section 2. In Section 3, we analyze the intrusion coverage intensity of K-set randomized scheduling algorithms when intrusion objects are abstracted to 2D and 3D shapes, respectively. In Sections 4 and 5, the results are extended to more realistic cases, in which sensor node deployment follows Gaussian distribution in a two-dimensional plane and a three-dimensional space, respectively. In Section 6, we focus on answering a few practical questions, such as how the size and shape of intrusion objects affect the detecting capability of sensor networks via performance evaluation using both analysis and computer simulations. Finally, we conclude our paper in Section 7.

2. Related work

Many efforts in WSNs have been dedicated to tracking and locating objects. In [32], a technique that employs the false discovery rate (FDR) procedure and belief propagation (BP) like algorithm is proposed for detection and localization problems in sensor networks. In [35], cooperative tracking, which combines acoustic information detected from neighboring sensor nodes and estimates the location of objects, was proposed as a method for tracking objects. In [28], the authors provided an upper limit to how far a mobile intrusion object can reach along a straight line within a dense wireless sensor network before it is detected.

According to the features of wireless sensor networks, energy consumption is an invariable problem in any application of wireless sensor networks. In [33], a semantic location-based data model for object tracking sensor networks was proposed in order to achieve network-wide energy optimization. The strategy directs data dissemination of and data extraction from sensor nodes in a power-efficient way. Meanwhile, to save energy, many researchers develop strategies that periodically switch off sensor nodes. In [29,31], the trade-offs between the speed of detecting the mobile object and the energy savings brought by turning many nodes into sleep mode were examined. In [29], the authors quantified the trade-off between power conservation and the quality of object tracking while presenting guidelines for efficient deployment of