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Analysis of stochastic coverage and connectivity in three-dimensional heterogeneous directional wireless sensor networks

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ABSTRACT

Coverage and connectivity are important factors that determine the quality of service of three-dimensional wireless sensor networks (3D WSNs) monitoring a field of interest (FoI). Most of the literature on the analysis of coverage and connectivity in 3D WSNs assumes the use of omni-directional sensors with spherical sensing regions. In this paper, we assume that the sensors are deployed uniformly at random in a FoI. We also consider a case when the sensors have only directional sensing capability and may have heterogeneity in terms of the sensing range, communication range, and/or probability of being alive. For such 3D heterogeneous directional WSNs, we derive probabilistic expressions for k-coverage and m-connectivity that are useful to optimize the cost of random deployment. We validate our analysis and demonstrate its benefits with numerical results. We also illustrate the application of this work for optimal design of a 3D heterogeneous directional WSN.
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1. Introduction

A three-dimensional wireless sensor network (3D WSN) consists of several tiny battery-powered sensors that can communicate with each other to monitor a 3D Field of Interest (FoI). WSNs monitoring a 3D FoI are commonly found in applications such as monitoring of wildlife habitats, where the sensors are deployed on trees in a forest at different heights [1], structural health monitoring of multi-storied buildings, underwater surveillance for oceanographic, marine life or coral reef monitoring [2], intelligent computer vision systems, constructing aerial defense systems, and building aerosphere pollution monitoring systems [3,4]. Most of the literature on 3D WSNs assumes the omni-directional sensing model [1,3,5–7] where a sensor can perfectly sense within the sphere of a given radius centred at the location of the sensor. However, there are many sensors in which the sensing region of the sensors is limited to a fixed direction and a specific angle. Examples of such sensors are camera sensors, multimedia sensors, infrared sensors, ultrasonic sensors, and radar sensors. A 3D WSN with such a type of sensors is called 3D *directional WSN* in the literature [8]. A directional sensor captures more accurate and comprehensive information for surveillance applications, smart environment applications, and location or positioning system. Fig. 1 illustrates a deployment of directional sensors uniformly at random in a 3D FoI to detect objects moving across the region. The events detected are then communicated to the sink. In this example, we assume infrared camera sensors being used to detect objects moving across the region. The sensors have limited view angle as depicted in the figure with sector in cross section.

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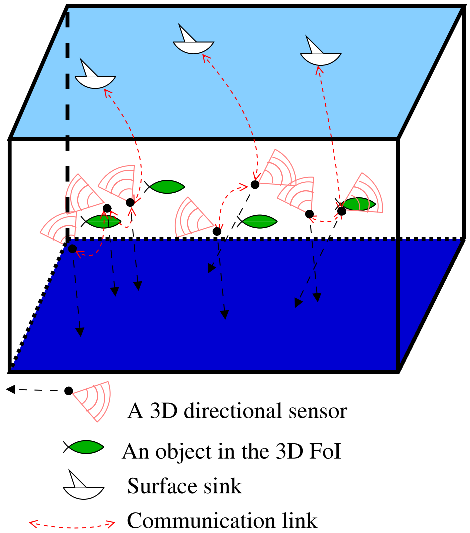

Fig. 1. Illustration of directional sensors deployed uniformly at random in a 3D FoI.

In some 3D WSNs where the location of the event is predictable or the region is easily accessible, the sensors could be deployed deterministically at fixed positions. On the other hand, random deployment of sensors is favored when the FoI to be monitored is hostile or inimical, and this is a popular assumption in the literature [5,9,10]. Due to random deployment of sensors in a hostile terrain, the sensors may fail or become faulty after sometime. A faulty sensor is prone to errors in detecting an event and the quality of service of the WSN depends on the probability of the sensors being alive (*i.e.*, non-faulty and reliable). The existing work on 3D WSNs assumes either that the probability of a sensor being alive is unity [1,5,11] or is constant for all the sensors [12–14]. In a large scale random deployment of sensors, this assumption is difficult to make. A limited battery power and difficulty in recharging/replacing the batteries in a hostile environment require that the sensors be deployed with a high density to prolong the lifetime of the WSN. In such a deployment, some inexpensive sensors have shorter sensing and communication ranges and perform only sensing, while a few expensive sensors provide sensing, sensory data fusion, and transport to the sink. In a practical scenario, all the sensors may not have the same sensing and communication ranges, and may not have the same probability of being alive. The sensing range of the sensors might be different due to the variation in the capabilities of hardware and imperfect sensing conditions. Such 3D WSNs are often called 3D *heterogeneous WSNs* (HWSNs) in the literature. The sensors in a 3D HWSN may be categorized into different types based on their sensing range, communication range, and/or the probability of being alive.

In any monitoring application, sensing coverage or simply *coverage* is acknowledged as an important metric to measure the quality of service of the WSN [15]. It specifies how well a FoI is monitored by the WSN. Any event that occurs in the FoI can be detected by a sensor if the location of the event is within its sensing region. In certain sensor network applications like intruder detection, it might be necessary to detect an intruder by at least k, $k \geq 1$ sensors to improve the accuracy of detection. Formally, a point in the FoI is said to be *k-covered* if it lies in the sensing region of at least k alive sensors. This is equivalent to point k-coverage defined in the literature [5]. *k-coverage ratio* defined as the ratio of the volume of the FoI in which each point is k-covered by the 3D WSN to the volume of the FoI is used to quantify the quality of coverage [5].

Connectivity is complementary to coverage and it indicates how well the data can be communicated by the sensors to the sink. When a sensor network is modeled as a graph with sensors as the vertices and the communication link between two sensors as an edge, a connected network means that the underlying graph is connected. A WSN is said to be m-connected if removal of any $(m-1)$ sensors does not render the underlying communication graph disconnected [16]. *m-connectivity probability* of the network is defined as the ratio of the sensors that are part of m-connected network to the sensors in the network [17,18]. It should be noted that quality, robustness, and throughput of a sensor network are directly related to the degree of coverage and connectivity.

In this work, we address the problem: *When a large number of heterogeneous directional sensors are deployed uniformly at random in a 3D FoI, what is the expected value of the k-coverage and the expected value of m-connectivity of the WSN?* We assume that sensors are heterogeneous in terms of sensing range, communication range, and/or the probability of being alive.

Major contributions: To the best of our knowledge, this is the first work to address the problem of determining k-coverage and m-connectivity in 3D WSNs with a stochastic deployment of sensors with heterogeneous and directional sensing capabilities. Along with this the major contributions of our work are as follows:

- We derive an expression to evaluate the expected value of the k-coverage ratio of the 3D FoI. Specifically, we estimate the probability of a point in the 3D FoI, being covered by at least k heterogeneous sensors. We consider the probabilistic directional sensing model.

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