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Coverage and connectivity in three-dimensional networks with random node deployment

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ABSTRACT

The increasing interest in using sensor networks in applications for underwater surveillance and oceanic studies underscores the importance of solving the coverage and connectivity issues in 3D wireless sensor networks (WSN). In particular, the problem of supporting full coverage, while ensuring full network connectivity is a fundamental one for such applications. Unfortunately, designing a 3D network is significantly more difficult, as compared to designing a 2D network. Previously, it has been shown that dividing a 3D space into identical truncated octahedral cells of radius equal to the sensing range and placing a sensor at the center of each cell, provides full coverage with minimum number of nodes [2]. But this requires the ability to deploy and maintain sensor nodes at such particular locations. In many environments, this is very difficult, if not impossible, to do. In this paper, we investigate the coverage and connectivity issues for such 3D networks, especially underwater networks, while assuming random and uncontrollable node locations. Since node location can be random, redundant nodes have to be deployed to achieve 100% sensing coverage. However, at any particular time, not all nodes are needed to achieve full sensing coverage. As a result, a subset of the nodes can be dynamically chosen to remain active at a time to achieve sensing coverage based on their location at that time. One approach to achieve this goal in a distributed and scalable way is to partition the 3D network volume into virtual regions or cells, and to keep one node active in each cell. Our results indicate that using cells created by *truncated octahedral tessellation* of 3D volume minimizes the number of active nodes. This scheme is fully distributed, and so it is highly scalable. By adjusting the radius of each cell, this scheme can be used to achieve *k*-coverage, where every point inside a network has to be within the sensing range of *k* different sensor nodes. We analyze and compare the performance of these schemes for both 2D and 3D networks. While for 1-coverage, the 3D scheme is less efficient than the 2D scheme, the performance of 3D scheme improves significantly as compared to 2D scheme for *k*-coverage, for values of *k* is larger than 1. As a result, such a distributed and scalable scheme can be more useful in 3D networks than in 2D networks. Although this paper targets in particular 3D underwater networks, much of our results are applicable to other 3D networks, such as for airborne applications, space exploration, and storm tracking.

1. Introduction

Applications of sensor networks for underwater applications such as exploitation, surveillance, oceanic

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study, (as well as in other applications such as space exploitation, airborne surveillance and greenhouse gas monitoring) require deployment of 3D wireless sensor networks. Although practical wide-scale deployment of 3D networks is still relatively limited, there has much work in progress that promises to make 3D networks significantly more ubiquitous in the not-so-far future. For example, underwater acoustic sensor networks have generated a lot of interest among researchers [1,11,15,19,38–41,43]. Ocean column monitoring requires the nodes to be placed at different depths of ocean, which creates a three-dimensional network [1]. In an article of Business 2.0 magazine, eight technologies have been identified that can save the world from global warming and its catastrophic consequences [13]. That article identifies environmental sensor networks as one of those eight technologies Since sensor nodes in such environmental wireless sensor networks will be distributed over a 3D space, they must be modeled as a 3D network as well.

Many detection and tracking applications require full coverage such that any point inside the network volume (also referred to here as network space) is monitored at any time by at least one sensor [5,9,12,23,25,33]. It is also important to maintain connectivity, so that detection information can be transmitted to the sink or a command center. While coverage and connectivity issues have been thoroughly investigated in the technical literature, the scope of most of those works relates to terrestrial 2D sensor networks. Unfortunately, many of those results cannot be directly applied to 3D networks. In fact, many widely used coverage analysis and placement strategies developed for 2D networks become NP-Hard in 3D [36]. It is not surprising, given the historical fact that many problems in 3D required many centuries of effort to be solved, while their 2D counterparts can be solved trivially. For example, Kepler's sphere packing problem has been around since 1611, but a proof of Kepler's conjecture has only been found in 1998 [17]. It is still an open problem if Kelvin's conjecture holds when the cells have identical shape. Similarity with Kelvin's conjecture has been used before to solve coverage and connectivity problem in 3D networks [2,3]. But these works are applicable only under the assumption that sensor nodes can be deployed and maintained at specified arbitrary locations. Although this assumption may be realistic in some communication environments, it could be consider less practical in large deployment of underwater sensor networks. In this paper, we investigate the coverage and connectivity issues in 3D networks where this latter assumption does not hold. Instead, we assume that we have no control over the movement of a node. As a result, the position of a node can be random and a large number of redundant nodes have to be deployed in order to ensure that every point of the network is within the sensing range of at least one sensor node. However, at any time instant usually not all nodes are needed for full sensing coverage. The challenge is to find a distributed and scalable scheme that dynamically selects a suitable subset of nodes to remain active based on their location, while putting other nodes into sleep mode. Since energy consumption during sleep mode is insignificant, this approach prolongs network lifetime significantly. Although it is possible to solve this problem in many different ways, however, finding a distributed and scalable scheme that adjusts in real-time with changes in the network topology (e.g., movement of nodes) is difficult [28]. Any solution that depends on a lot of message passing is unlikely to achieve this objective, especially because of the particular characteristics of the underwater communication environment.

In this paper, we propose a very fast, distributed, and scalable scheme to dynamically select a subset of active nodes, such that full sensing coverage and connectivity is always maintained. We assume that sensing and communication range of each sensor node is deterministic, homogeneous, and spherical. It is also assumed that each sensor node has a localization component that allows it to determine its position. (Such schemes have been studied extensively in the technical literature; see e.g., [44–46].) The main idea is to divide the 3D network space into identical regions based on the sensing range and communication range of the sensor nodes. Among the sensor nodes located in each region, one sensor node is dynamically and locally selected to perform the sensing operation for that region and to maintain connectivity with active nodes of the neighboring regions.

Although this general idea has been used before [34], the challenging part is to determine the best possible division that minimizes the number of regions (and thus minimizes the number of active nodes at any time). There are two constraints here. First, the diameter of the circumsphere of each region cannot be greater than the sensing range of each sensor node. This is because, unlike in [2,3], we do not have any control of the position of the node. In the extreme case, it is possible that the selected active node is located in one corner of the region. Still this sensor node must be able to sense all the points of its region. Second, maximum distance between two furthest points of the neighboring regions cannot be greater than the communication range of each sensor node. This constraint guarantees that active nodes of two neighboring region are able to communicate between them, irrespective of their positions inside each region. These two constrains ensure that full coverage and connectivity are maintained even though active nodes are selected locally by the nodes inside each region.

Our contributions, results, and conclusions of this work can be summarized as follows:

- We investigate the problem of coverage and connectivity for 3D networks where deployment of a node at any predetermined position and maintaining that node position cannot be ensured. As a result, a large number of nodes have to be randomly deployed. Since at any particular time, all nodes are not needed for maintaining full sensing coverage and connectivity, it is important to put the redundant nodes into sleep mode, thus limiting the energy use and prolongs the network lifetime. This must be done in a dynamic fashion based on the position of the nodes at that instant. The scheme must be highly distributed and scalable, because node movement is unpredictable. We introduce such a scheme that dynamically determines the active node locally.