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Layered Diffusion-based Coverage Control in Wireless Sensor Networks

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A B S T R A C T

Coverage is an important performance metric for many applications, such as surveillance in wireless sensor networks. Coverage control is used to select as few active nodes as possible from all deployed sensor nodes, such that sufficient coverage of the monitored area can be guaranteed while reducing the energy consumption of each individual sensor node to prolong the network lifetime. This paper classifies three types of coverage control protocols based on the available information about nodes' distances or locations, and reviews several representative protocols for each type. We also propose a new distributed and localized coverage control protocol, called Layered Diffusion-based Coverage Control (LDCC). The LDCC protocol does not require information about the node location coordinates when selecting active nodes. Instead, it exploits hop count information, which is easily obtained in a WSN, to select active sensor nodes. Furthermore, the LDCC protocol is very simple and does not require any sophisticated computation such as distance or covered area computation. Our simulation results show that the LDCC protocol achieves a high coverage ratio while incurring very low message overhead compared with other existing protocols. Furthermore, simulation results suggest that in a large-scale sensor network with medium to large localization errors, LDCC performs even better than location-based coverage control protocols.

1. Introduction

Recent advances in micro-electro-mechanical systems, embedded processors, and wireless communications have given rise to *Wireless Sensor Networks* (WSNs), which consist of a large number of sensing devices, each capable of sensing, processing and transmitting environmental information. Applications of WSNs include battlefield surveillance, environmental monitoring, biological detection, smart spaces, industrial diagnostics, and so on [1].

A fundamental issue in WSNs is the *coverage problem* [2,3]. In general, coverage determines how well a sensor field is monitored by sensors. In the literature, a widely used sensing model assumes that a sensor can cover a disk centered at itself with a radius equal to a fixed sensing range. In this paper, we also adopt this sensing disk model and use R_s to denote the sensing range. In some applications, the field to be monitored is remote and dangerous, and sensors may have to be randomly deployed from (for example) an aircraft. In randomly deployed sensor networks, the number of sensor nodes is generally higher than the optimum in order to guarantee complete area coverage or achieve a certain network robustness. A sensor is called redundant if its covered (sensed) area can also be covered (sensed) by other sensors. Therefore, it is not necessary to let every node activate its sensing unit all the time, and sensor activity scheduling can be used to schedule sensors to be activated alternatively. In the literature, many localized and distributed coverage control protocols have been proposed to schedule sensor sensing activity only based on local message exchange. Although these protocols have the same objective, i.e., to prolong network operation time and guarantee certain area coverage requirements, they make

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different assumptions about the available information regarding the sensor network, and hence their approaches and performances are also different.

The main information used in a coverage control protocol includes the distance information between two neighboring nodes and the locations of neighboring nodes. Based on the availability of the distance and location information, we classify the existing coverage control protocols into three groups. In the first group, nodes' location information is required for the protocol design, and each node is assumed to know its own location. In the second group, only node-to-node distance information is required in the protocol design, while the nodes' location information is not required. In the third group, the protocol design does not use any nodes' distance and location information. Note that knowledge of the nodes' locations can be used to derive distances between any pair nodes, but knowledge of the distance information may not be enough to derive the nodes' locations. Hence, knowledge of nodes' locations is the strictest requirement, followed by knowledge of nodes' distances.

Ranging is used to estimate the Euclidean distance between two nodes, and some typical ranging methods include the use of the measurements of time-of-arrival, angle-of-arrival, received-signal-strength and so on. Localization is used to estimate the nodes' Cartesian coordinates. In a large-scale sensor network, in general, a few *anchor* nodes are assumed to know their own coordinates (for example, via GPS) and other nodes' coordinates are derived based on these anchor nodes and some particular node localization technique. Many localization techniques have been proposed for WSNs, and we refer the reader to [4] for a comprehensive survey. Ranging and localization are far from perfect in practice, and different techniques may introduce different types of ranging and localization errors. Some authors have studied such errors and their impacts on path coverage problems [5,6]. However, for area coverage problems, little work has been done to compare coverage control protocols under ranging and localization errors.

In this paper, we present the design of a new distance- and location-free coverage control protocol, called Layered Diffusion-based Coverage Control (LDCC), which is motivated by the triangular tessellation. LDCC exploits only hop count information, and applies the layered diffusion technique to dynamically emulate a triangle tessellation process and to control the sensor nodes' sensing activity. The LDCC protocol needs only very simple computation and has low control message overheads. The effectiveness of LDCC is validated and its performance is compared with several typical existing protocols via simulations. Simulation results show that, among distance- and location-free protocols, LDCC achieves a high coverage ratio with a lower number of selected active nodes. Although the location-based coverage control protocol (OGDC) performs best when there are no localization errors, its performance degrades quickly when the location error increases and its performance is even worse than the proposed LDCC when the localization errors are above half of the sensing range.

The rest of the paper is organized as follows: we briefly review representative coverage control protocols of each group in Section 2. Section 3 presents the LDCC protocol design and Section 4 provides our simulation results. The paper concludes in Section 5 with some further discussions.

2. Coverage control protocols

2.1. Location-based coverage control protocols

The simplest way to obtain location information is to equip each node with a GPS device. However, this might be much expensive. For resource-limited sensor networks, many node localization algorithms have been proposed. For example, a node estimates its distances to some anchors with known locations and then applies trilateration or multilateration to compute its location. Assuming that the nodes' locations are known, many coverage control protocols have been proposed to schedule sensor activity based on sensor redundancy checks. For example, Tian and Georganans [7] propose a concept of *sponsored sector* for checking redundancy; Huang et al. [8] propose to use *perimeter coverage* to check field complete coverage and sensor redundancy; Xing et al. [9] apply *crossing coverage* to determine redundant sensors; and Cărbunar et al. [10] propose to use *Voronoi diagram vertices and intersections* to check redundancy. All these redundancy checking algorithms require knowledge of nodes' locations in the computation. Based on the redundancy check, a distributed coverage control protocol can be established as follows. At first, all sensors are active and each sensor checks its redundancy. A non-redundant sensor sets its state as active. A redundant sensor enters the sleep state after a random back-off time and broadcasts a notification message. All sensors that receive such a message will re-check its redundant eligibility and the process repeats until every node decides its state.

Besides letting redundant sensors become inactive sequentially, a counterpart method is to activate proper sensors sequentially. Zhang and Hou [11] propose an *Optimal Geographical Density Control* (OGDC) scheduling scheme based on a triangle tessellation process. It is well-known that putting sensor nodes at the vertices of an equilateral triangle lattice requires the least number

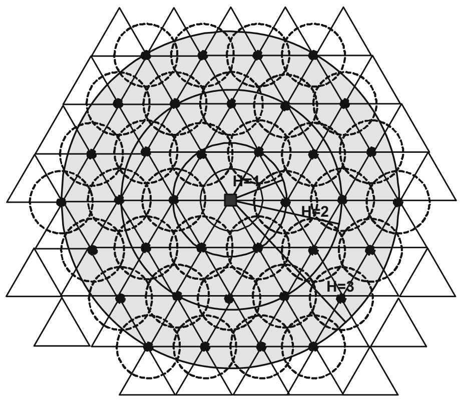

Fig. 1. Illustration of system model and triangular tessellation.