Lightweight Deployment-Aware Scheduling for Wireless Sensor Networks

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Abstract. Wireless sensor networks consist of a large number of tiny sensors that have only limited energy supply. One of the major challenges in constructing such networks is to maintain long network lifetime as well as sufficient sensing areas. To achieve this goal, a broadly-used method is to turn off redundant sensors. In this paper, the problem of estimating redundant sensing areas among neighbouring wireless sensors is analysed. We present simple methods to estimate the degree of redundancy without the knowledge of location or directional information. We also provide tight upper and lower bounds on the probability of complete redundancy and on the average partial redundancy. With random sensor deployment, our analysis shows that partial redundancy is more realistic for real applications, as complete redundancy is expensive, requiring up to 11 neighbouring sensors to provide a 90 percent chance of complete redundancy. Based on the analysis, we propose a scalable Lightweight Deployment-Aware Scheduling (LDAS) algorithm, which turns off redundant sensors without using accurate location information. Simulation study demonstrates that the LDAS algorithm can reduce network energy consumption and provide desired QoS requirement effectively.

Keywords: scheduling, coverage, wireless sensor networks

1. Introduction

Large-scale wireless sensor networks rely on thousands of tiny sensors to observe and influence the physical world [1,7,19]. The sensors can monitor surrounding environment, carry out simple calculation, and communicate with each other through short-range radio transmission. When clustered together, these sensors automatically create highly flexible, low-power networks with applications ranging from building control systems to smart entertainment devices that adjust audio and video quality based on their surroundings.

While the application potential of wireless sensor networks is limitless, power supply to thousands of sensor nodes is extremely challenging. Each sensor node is usually powered by battery and is expected to work for several months to one year without recharging. Such expectation cannot be achieved without carefully scheduling the energy consumption, especially when sensors are deployed densely (high up to 20 nodes/m^3 [14]), with severe problems of scalability, redundancy, and radio channel contention.

Fortunately, the high density of sensors provides us with much room to design energy efficient protocols. A broadly-used strategy for reducing energy consumption in wireless sensor networks is to turn off redundant sensors by scheduling sensor nodes to work alternatively [16,22]. The heuristic of utilising nodes’ redundancy has also been used in wireless ad hoc networks [2,9,20] and usually depends on location or directional information such as that obtained with the Global Positioning System (GPS) and the directional antenna technology. The energy cost and system complexity involved in obtaining geography (location, direction, or distance) information, however, may compromise the effectiveness of proposed solutions as a whole. Furthermore, it is still a very difficult problem to estimate sensors’ locations, since GPS and other complicated hardware devices consume too much energy and the costs are too high for tiny sensors. It

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is expected that scheduling algorithms should work without any geography information.

Without accurate geography information, however, it is very hard to check whether a sensor’s sensing area can be completely covered by other sensors. As a result, turning off sensors may generate blind points that cannot be monitored by any sensor. Fortunately, most applications may not require complete coverage of the monitored area. For example, for office temperature monitoring, we may only need to obtain temperature readings from each corner of the office. Sensor networks will still be effective for most applications as long as a reasonable coverage is maintained. Because of this reason, it is critical to provide good scheduling algorithms to turn off sensors without degrading sensing coverage significantly in a statistical sense.

In order to achieve the above research goal, it is necessary to answer the following question first: under what conditions and with what probability a sensor is redundant or partially redundant? In this paper, we propose a mathematical model to describe the redundancy in randomly deployed sensor networks. We base our analysis on random deployment since this deployment strategy is easy and cheap for large sensor networks [17]. We present simple formulae to estimate the probability that a sensor is completely redundant and to estimate the average partial redundancy. Based on theoretical analysis, we propose a Lightweight Deployment-Aware Scheduling (LDAS) scheme to turn off redundant sensors. LDAS uses a weighted random voting method to decide whether sensors without degrading sensing coverage will be eligible to fall asleep.

Although the estimation of redundancy has been studied by simulation [9], to the best of our knowledge, there is no paper presenting a thorough analysis for such an estimation. Our analytical results will benefit the research in wireless sensor networks by providing simple formulae to estimate sensor redundancy. They can be utilised in designing deployment-aware scheduling scheme to save energy consumption. Different sensor deployment strategies can cause very different network topology, and thus different degrees of sensor redundancy. The knowledge for sensor deployment, however, is usually available in advance. For instance, it is easy to know the number of sensors and how the sensors are dispatched for a particular application. Unlike methods based on geography information, scheduling algorithms solely based on deployment knowledge do not require additional energy cost to obtain location information and present a promising research direction. We expect our work could stimulate more research along this direction.

The rest of the paper is organized as follows. Section 2 presents preliminary definitions and a mathematical model for the analysis of sensor redundancy. In Section 3, we present detailed analysis on two sensor redundancy problems. Based on the analytical results, we propose a Lightweight Deployment-Aware Scheduling (LDAS) scheme in Section 4 and perform simulation study in Section 5. We introduce related work in Section 6 and finally conclude the paper in Section 7.

2. Preliminaries

We assume sensors are deployed randomly with uniform distribution within an area. A sensor’s sensing range is a circular area centred at this sensor with a radius of \( R \). Also, we assume all sensors lie on a 2-dimensional plane. The analytical results in this paper, however, can be easily extended to 3-dimensional space. In addition, all sensors are supposed to have the same sensing range and no two sensors are deployed exactly at a same location in the 2-dimensional plane.

Definition 1 (Neighbour [16]). The 1-hop neighbour set of sensor \( i \) is defined as

\[
N(i) = \{ j \in \mathbb{N} | d(i, j) \leq R, i \in \mathbb{N}, j \neq i \}
\]

where \( \mathbb{N} \) represents the sensor set in the deployment region, \( d(i, j) \) denotes the distance between sensor \( i \) and sensor \( j \), and \( R \) is the radius of the sensing range. If sensor \( m \) is not sensor \( i \)’s 1-hop neighbour but is within the sensing ranges of sensor \( i \)’s 1-hop neighbours, sensor \( m \) is called a 2-hop neighbour of sensor \( i \).

Definition 2 (Completely and partially redundant sensor). Let \( C_i \) be the sensing area of sensor \( i \). If \( \cup_{j \in N(i)} C_j \geq C_i \), we call sensor \( i \) a completely redundant sensor, since sensor \( i \)’s sensing area can be covered by its 1-hop neighbours completely. If \( \cup_{j \in N(i)} C_j \) can cover only part of \( C_i \), that is, \( \cup_{j \in N(i)} (C_j \cap C_i) \neq \emptyset \) and \( \cup_{j \in N(i)} \frac{C_j}{C_i} \), we call sensor \( i \) a partially redundant sensor.

In this paper, we only consider a sensor’s 1-hop neighbours, even if a partially redundant sensor may be completely covered by its 1-hop plus 2-hop neighbours. Obtaining and maintaining 2-hop neighbourhood information need large storage cost and will make calculation more difficult. High cost of memory and calculation wastes energy and violates our original research motivation in investigating the redundancy problem. Without causing confusion, in the rest of the paper, neighbours will be referred to 1-hop neighbours only.

Definition 3 (Quality of Service (QoS)). The Quality of Service (QoS) of sensor networks is defined as the percentage of a given deployment region that can be monitored. Turning off completely redundant sensors will save energy consumption without degrading QoS. Nevertheless, without accurate geography information, it is very difficult to check whether a sensor is completely redundant. Therefore, it is critical to propose good heuristics based on which turning off sensors would not degrade QoS largely.

Definition 4 (Sponsored sector and effective angle [16]). Suppose node \( O \) and node \( X_1 \) are neighbours. As shown in figure 1, the sector, bounded by radius \( O P_1 \), radius \( O P_2 \), and the inner arc \( P_1 P_2 \), is called the sponsored sector by node \( X_1 \) to node \( O \), and is denoted as \( S_{X_1 \rightarrow O} \). \( P_1 \) and \( P_2 \) are two intersections of edges of \( O \)’s and \( X_1 \)’s sensing areas and are arranged in the counter-clockwise order. In the rest of this paper, \( P_1 \) and \( P_2 \) are also called respectively the first and the...