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Periphery deployment for wireless sensor systems with guaranteed coverage percentage

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ABSTRACT

With the availability of tiny wireless sensors, it is now possible to track moving objects by placing such sensors on the targets, collecting needed data, and transmitting sensed data back to the sink for storage and analysis. For applications such as vessel clearance surveillance, landslide detection, conveyer monitoring, and body gesture tracking, the motions of the targets are often confined to a certain region, such as the water way or the mountain slope. To collect the data from the wireless sensors, base stations are usually needed, which are deployed at fixed positions around the monitored region. Unfortunately, due to issues such as potential interference, high packaging and deployment cost, and low reliability, many such applications could only deploy the base stations on the periphery of the monitored region. The question is how to deploy the base stations on the periphery so that they can cover the most area inside the monitored area. We formulate the *periphery deployment problem* and analyze the performance bound in terms of coverage percentage under both ideal and practical deployment conditions. Then, we describe a deployment procedure to solve the periphery deployment problem in polynomial time. The proposed algorithms are evaluated through extensive simulations drawn from a watercourse monitoring system. The results show that the proposed algorithms can reduce the size of the deployment set by 17% compared to the traditional area-coverage algorithms, and the coverage percentage is improved by 1.18 times.

1. Introduction

With the availability of tiny wireless sensors, it is now possible to track moving objects by placing such sensors on the targets, collecting needed data, and transmitting sensed data back to the central station for storage and analysis (Cardei et al., 2008; Liu and Ssu, 2008). For example, to monitor debris flows, existing systems only use point and indirect means to measure information regarding the flows. With wireless sensors, it is now possible to perform in situ and direct tracking of debris flows in real-time (Lee et al., 2009, 2008). The idea is to through wireless sensors into the debris flows as shown in Fig. 1. To collect the sensed data from the wireless sensors for real-time processing, base stations are deployed at fix locations on the riverbank. When a debris flow runs upstream, sensors on the riverbed are carried by the flow, and base stations along the riverbank collect sensed data from the sensors as they pass by.

In this application, base stations cannot be deployed in the waterway. Otherwise, they will be destroyed easily by the debris flows. The best strategy is to deploy the base stations on the riverbank, or the periphery, of the monitored region. Assume that the data collection between wireless sensors and base stations utilize single-hop communication. If wireless sensors only move within the monitored region, the question is how to deploy the base stations so that they can cover the maximum area in the monitored region. In this paper, we will use the term "*track*" to represent the monitored region, in which the targets, as well as the wireless sensors they carry, may move around.

Coverage is a fundamental problem in *wireless sensor networks* (WSNs). An intuitive solution is to deploy the base stations inside the track to fully cover the track. Many previous works have studied the full coverage problem (Bai et al., 2006, 2008b). However, for applications such as debris flow surveillance, we cannot deploy base stations inside the track. Besides, contrarily to previous work, we both consider mobile sensors and single-hop communication between wireless sensors and base stations. Similar applications include water surveillance (Pompili et al., 2006), capturing human body movements (Aylward and Paradiso, 2007), conveyer monitoring (Pang and Lodewijks, 2006), and landslide detection (Terzis et al., 2006). The base stations may interfere with the monitored targets if they were deployed inside the track, and the cost of such deployment methods may be very high, e.g., requiring extra

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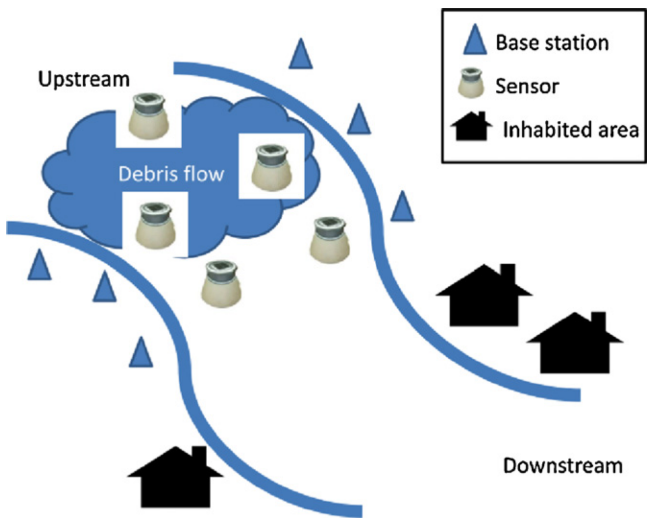

Fig. 1. System architecture of a debris flow surveillance system.

water/crash proof (Pompili et al., 2006) or protection packages (Pang and Lodewijks, 2006). If base stations can only be deployed on the periphery of the track, what is the best deployment strategy?

A possible solution is to set tracks as obstacles and then adopt area-coverage algorithms (Bai et al., 2008a; Kang and Chen, 2009) to deploy the base stations. However, this strategy may try to cover areas where no data needs to be collected, wasting the deployed base stations. A good solution to the *periphery deployment problem* must consider a number of important factors, including how many base stations are required, where they are deployed, and how they affect the system performance. In this paper, we first formally define the periphery deployment problem. To the best of our knowledge, this is the first work that addresses the problem of deploying base stations *outside* the tracks for collecting data from mobile sensors moving *inside* the tracks. Second, we analyze the upper bound of the coverage percentage mathematically under ideal deployments and the average coverage percentage under practical deployments. A deployment procedure is then proposed to solve the periphery deployment problem. The proposed algorithms are evaluated by extensive simulations draw from a watercourse surveillance system. The results show that the proposed algorithm outperforms traditional area-coverage algorithms in terms of coverage percentage and number of base stations required.

The remainder of the paper is organized as follows. Section 2 contains a review of related works. In Section 3 we present the problem statement, system models, and some formal definitions. In Section 4, we analyze the maximal coverage percentage of the proposed periphery deployment model. We discuss the deployment procedure in Section 5, and evaluate the performance of the algorithms in Section 6. Then, in Section 7, we summarize our conclusions and consider future research directions.

2. Related work

In this paper, we focus on deployment problems in WSNs, a topic that has attracted a great deal of attention in recent years. There has been much research on the sensor coverage problem. Most works formulate deployment problems as coverage problems and study the coverage percentage of monitored regions. The coverage area of a single sensor is usually defined based on the sensing range or communication range, or both. The major design goal of existing algorithms is to cover the whole monitored regions with the least cost.

For a monitored region containing obstacles, Dhillon and Chakrabarty (2003) proposed two algorithms to maximize the coverage area. By checking all possible grid points, sensors are deployed in an incremental manner based on two utilization functions. The MAX_AVG_COV algorithm deploys sensors in such a way that the average coverage of the grid points is maximized. The MAX_MIN_COV algorithm tries to maximize the coverage of grid points where the coverage is not complete. Wu et al. (2007) proposed a deployment algorithm based on Delaunay triangulation. The proposed DT-Score scheme first considers coverage holes near the boundary of monitored regions and obstacles. Uncovered regions are then considered. Each candidate location for deploying sensors is scored by a probabilistic detection model. The sequence for deploying sensors is then determined by the proposed evaluation function. Lin et al. (2008) developed an analytical model that derives the expected coverage by deploying camera sensors randomly. Based on the model, they propose an adaptive deployment strategy to decide the number of sensors. Carter and Ragade (2009) introduced a probabilistic model to calculate the detection probabilities of sensors. A coverage matrix is then defined and optimized with a genetic algorithm. Some deployment strategies consider the sensing coverage as well as the communication coverage. The degree of communication coverage affects both network topology and sensor connectivity. Kershner (1939) proved that a triangular pattern is asymptotically optimal in terms of the number of discs used to ensure full coverage. The pattern provides a connectivity of six when the ratio between the communication range and sensing range is larger than or equal to $\sqrt{3}$. More recently, various patterns have been proposed to achieve one-, two-, and four-connectivity for full coverage (Bai et al., 2006, 2008b; Iyengar et al., 2005). To generate the patterns discussed in those studies Bai et al. (2008a) proposed using a hexagon-based elemental pattern, which achieves full coverage and k connectivity ($k \leq 6$). In these works, sensing coverage or communication connectivity is an area-based concept and the deployment problem is to cover the monitored region with sensing or connectivity constraints by deploying sensors inside the monitored region, i.e., the track. On the other hand, our work considers the deployment of base stations on the periphery of the monitored region. We mainly address the coverage achieved by base stations. Candidate locations for deploying the base stations and the coverage of the monitored regions are quite different from the previous works.

Some works consider redeployment problems. Zou and Krishnendu (2003) propose a virtual force algorithm to improve sensing coverage after an initial deployment by moving sensors to new locations. A combination of attractive and repulsive forces is used to determine new locations for sensors. Shu and Liang (2005) developed a fuzzy algorithm to adjust sensor locations, taking into account the uncertainty of deployment processes. In these works, the number and locations of sensors are known; however, in our work, we have to determine the number of base stations as well as their locations.

Many approaches consider extra constraints in addition to the coverage requirement. Maleki and Pedram (2005) studied sensor density based on both sensing coverage and energy constraints. The sensor density is first determined based on coverage constraint, after which sensors are deployed according to a continuous space model. The continuous space model is designed for random deployment with associated routing scheme to provide the minimum energy consumption. In the debris flow surveillance system, base stations usually play the role of bridges between wireless sensors and the Internet. Base stations are always equipped with sufficient power supplies, so energy consumption is not an essential issue in