J. Parallel Distrib. Comput. 89 (2016) 37–49

Contents lists available at ScienceDirect

J. Parallel Distrib. Comput.

journal homepage: www.elsevier.com/locate/jpdc

A unified framework for *k*-coverage and data collection in heterogeneous wireless sensor networks

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HIGHLIGHTS

- This work considers heterogeneous sensors and sink mobility, which provide a more realistic and accurate view of the network design for a variety of sensing applications.
- This work exploits Helly's Theorem to address the joint problem of *k*-coverage and data collection in heterogeneous wireless sensor networks, where each point in a field of interest is simultaneously covered by at least k active heterogeneous sensors.
- This work investigates the optimal mobility strategy of the sink in order to minimize the average total energy consumption due to both of data communication and sink mobility in a circular sensor field.

ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form
23 August 2015
Accepted 27 September 2015
Available online 3 November 2015

Keywords:
Wireless sensor nets
k-coverage
Data collection
Heterogeneity
Hierarchical deployment
Adaptive forwarding
Sink mobility
Helly's theorem

ABSTRACT

One of the fundamental tasks in the development of wireless sensor networks is coverage, which measures the network effectiveness and accuracy in event detection. While most existing studies on coverage focus on homogeneous and static wireless sensor networks, where the sensors have the same features, such as sensing, communication, and initial energy reserve, this paper considers heterogeneous sensors and sink mobility, which provide a more realistic and accurate view of the network design for a variety of sensing applications. In this paper, we exploit Helly's Theorem to address the joint problem of *k*-coverage and data collection in heterogeneous wireless sensor networks, where each point in a field of interest is simultaneously covered by at least *k* active heterogeneous sensors. More precisely, we introduce a global framework that jointly considers *k*-coverage and data collection. Precisely, we propose a multi-tier (or hierarchical) architecture of heterogeneous sensors along with two data collection protocols. While the first protocol is based on an adaptive hybrid forwarding scheme, the second one uses a mobile sink to collect the sensed data from all the sensors in the network. To this end, we investigate the optimal mobility strategy of the sink in order to minimize the average total energy consumption due to both of data communication and sink mobility in a circular sensor field. We divide the field into concentric circular bands with the same width, and derive a closed-form solution for the optimal sink mobility. We corroborate our analysis with simulation results to assess our proposed framework. We find that our sink mobility-based data collection protocol outperforms our hybrid geographic forwarding-based data collection protocol.

1. Introduction

A wireless sensor network (or simply *sensor net*) consists of tiny, low-powered sensors that communicate with each other (possibly) in a multi-hop fashion and report their sensed data to a central gathering component, called the *sink*, for further analysis and processing. Sensor nets can be used in a wide variety of civilian, environmental, natural, and military applications, such as health monitoring, environmental monitoring, seismc monitoring, and battlefields surveillance, respectively. The design of sensor nets faces a major problem due to the very scarce resources of the sensors, such as battery power (or energy), bandwidth, CPU, and storage, to name a few, with energy being the most critical one.

Coverage and connectivity have been always considered among the major research problems in sensor nets [33]. While coverage informs how well a field is monitored, connectivity is concerned with how well sensors in a network communicate with each other. A more general concept of coverage is called *k-coverage*,

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http://dx.doi.org/10.1016/j.jpdc.2015.09.009
0743-7315/

where each point in a field is covered (or sensed) by at least k sensors simultaneously (or simply k-covered). The problem of joint k-coverage and data collection in sensor nets is one of the fundamental research problems in sensor nets. An efficient solution to the problem of k-coverage in sensor nets consists of finding a minimum subset of sensors S such that each point in a field is *k-covered* by sensors in S. Although the connected k-coverage problem in sensor nets has been studied extensively in the literature [5,12,13], most existing work focused on homogeneous sensor nets, where all the sensors have the same capabilities with regards to their storage, computational power, sensing range, communication range, and initial energy, to name a few. Also, the problem of k-coverage-preserving scheduling (or sensor duty-cycling) in homogeneous sensor nets has gained considerable attention [3,26,28,33,34]. However, this type of homogeneous sensors poses a severe restriction on the design of real-world sensor net applications given that all the sensors are required to have the same above-mentioned capabilities. In general, this assumption is unrealistic as the sensors may not necessarily have the same capabilities even when they are built by the same company. In other words, sensors may be heterogeneous.

1.1. Motivations

Our work is motivated by the following observations. First, in real-world applications, sensor nets have heterogeneous sensors which do not necessarily have the same capabilities (*i.e.*, sensing range, communication range, energy, storage, computation, etc.). These networks have a potential to increase the network lifetime and reliability without causing significant increase in their cost [30]. For instance, Intel deployed two types of sensors (line-powered and battery-power sensors) in the design of a pilot application of sensor nets in order to monitor the health of mechanical equipment in its fabrication plants [30]. While line-powered sensors can be attached to pumps and motors in the fabrication plant, battery-power sensors can be used to reduce installation cost and complexity. Indeed, Yarvis et al. [30] presented several analytical, and testbed results showing the potential benefit and impact of energy and heterogeneity on sensor nets, where all the sensors report their data to a sink. Second, the design of sensor nets for planet exploration [24], multiple-sensor data fusion [15], and triangulation-based positioning systems [23], requires degree of coverage $k \geq 3$. Third, the use of static sink potentially yields the problem of energy sink-hole, where the sensors around the sink are continuously involved in forwarding data on behalf of all other sensors to the sink. This causes a severe problem of depletion of their battery power (or energy), thus, isolating the sink. To remedy this problem, we use a mobile sink for data collection.

1.2. Problem formulation

In this paper, we consider heterogeneous sensors deployed in a field of interest. These sensors may differ by their sensing range, communication range, and/or energy reserve. More specifically, we focus on the problem of joint k-coverage and data collection in heterogeneous sensor nets using a single mobile sink. This problem can be stated as follows:

Given a deployment field and a set S of heterogeneous sensors, we want to address the following questions:

- How to select a minimum subset of sensors $S' \in S$ to stay active, and how to place them in the field so that each point in the field is k-covered, where $k \geq 3$ is the degree coverage needed by the sensing application?
- What is the optimal mobility trajectory of the sink so as to minimize the average total energy consumption due to data communication and sink mobility?
- How can data be collected efficiently in this type of duty-cycled k-covered sensor net?

It is worth mentioning that the problem of selecting a minimum subset of sensors to k-cover a field using homogeneous sensors is NP-hard [12]. With heterogeneous sensors, this problem is also NP-hard. Intuitively, the NP-hardness in the homogeneous case leads to the NP-hardness in the heterogeneous case. Thus, we propose approximation algorithms to solve the joint k-coverage and data collection problem in heterogeneous sensor nets with one mobile sink.

1.3. Major contributions

Our contributions in this paper can be described as follows:

- First, we propose a general framework for k-coverage and mobile data collection in sensor nets using a single mobile sink. This framework accounts for heterogeneous sensors, which do not have the same sensing range, communication range, and initial energy. Precisely, we propose centralized and distributed protocols for generating energy-efficient k-coverage configurations in heterogeneous sensor nets and data collection via a mobile sink. Precisely, we suggest a pseudo-random (*i.e.*, not fully random) sensor deployment approach, where the sensors are deployed in different layers in a circular sensor field according to their strengths with regard to their sensing range, communication range, and initial energy. Then, we propose energy-efficient centralized and distributed k-coverage protocols based on this pseudo-random deployment approach.
- Second, we suggest a data collection protocol based on an adaptive hybrid forwarding scheme, where the sensors could *adaptively* choose between short-range and long-range forwarding based on their location with respect to the sink. Moreover, as it is *hybrid*, the sensors take advantage of deterministic and opportunistic forwarding by specifying in their sensed data packets the id's of m active candidate next forwarders from their communication neighbor set, where $m > 1$.
- Third, we investigate the optimal mobility strategy of the sink during data collection with a goal to minimize the average total energy consumption due to data transmission and reception as well as sink mobility in a circular sensor field. To this end, we divide the field into concentric circular bands with the same width, and derive a closed-form solution for the optimal sink mobility. We use this analysis to design a data collection protocol using a mobile sink on top of our multi-tier sensor deployment architecture. To the best of our knowledge, this paper provides the first analysis of the best mobility trajectory of the sink during data collection in heterogeneous k-covered sensor nets.
- Fourth, we corroborate our analysis with simulation results to assess the performance of our framework. We find that our sink mobility-based data collection protocol outperforms our adaptive hybrid geographic forwarding-based data collection protocol. In addition, we find that our pseudo-random sensor deployment outperforms random sensor deployment to ensure k-coverage. Also, we find that our sink mobility-based data collection protocol outperforms our hybrid geographic forwarding-based data collection protocol in terms of average delay and data delivery ratio.