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Critical density for coverage and connectivity in two-dimensional fixed-orientation directional sensor networks using continuum percolation

Mohammad Khanjary [a,*], Masoud Sabaei [b], Mohammad Reza Meybodi [b]

[a] Computer and Electrical Engineering Department, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Computer Engineering and Information Technology Department, Amirkabir University of Technology, Tehran, Iran

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ABSTRACT

Given an initially uncovered field, and as more and more directional sensors (sensors with sector shape sensing area) are continuously added to the sensor network, the size of partial covered areas increases. At some point, the situation abruptly changes from small fragmented covered areas to a single large covered area. This abrupt change is called the sensing-coverage phase transition (SCPT). Likewise, given an originally disconnected sensor network, as more and more sensors are added, the number of connected components changes such that the sensor network suddenly becomes connected. This sudden change is called the network connectivity phase transition (NCPT). Such phase transitions occur in a certain density which is called critical density and finding it is a central topic of Percolation Theory. In this paper, we introduce fixed-orientation directional sensor networks (FIODSNs) and analytically compute critical density of nodes for both SCPT and NCPT in FIODSNs, for all field-of-view angles between 0 and π using continuum percolation. In FIODSNs which are the most common type of directional sensor networks, sensor nodes are deployed based on Poisson Point Process, and orientation of them is distributed between 0 and 2π, independently and uniformly. Due to percolation theory, the critical density is the infimum density for densities above it SCPT and NCPT almost surely occur. Therefore, the results could be used to prepare coverage and connectivity in FIODSNs. Moreover, to solve the SCPT and NCPT problems together, we propose a model for percolation in directional sensor networks which could be used in other related researches.

1. Introduction

Sensing coverage can be considered as one of the main criterion of quality of service in sensor networks. Extensive researches have been done to solve technical problems related to coverage in sensor networks and several types of coverage have been introduced by researchers so far. Network connectivity, on the other hand, is a graph-theoretic concept that helps sensors communicate with each other for forwarding their data to a central gathering node, called the sink. To sense a region of interest sufficiently and receive the sensed data by the sink, it is necessary that both sensing coverage and network connectivity be maintained. Due to wide range of technical problems in sensing coverage and network connectivity and also their significance, a lot of researches have been focused on them. Some recent reviews on different issues of coverage and connectivity in general sensor networks could be found in Ghosh and Das (2008), Wang (2011) and Zhu et al. (2012) and in directional sensor networks could be found in Guvensan and Yavuz (2011) and Charfi et al. (2009).

One of the main challenges about coverage and connectivity in sensor networks, is finding a certain density that coverage and connectivity almost surely occur for densities above it. Finding such densities is the main topic in Percolation Theory. In other word, the main topic in Continuum Percolation is finding the critical density of a Poisson point process at which an unbounded covered/connected component almost surely appears in the network. Percolation Theory prepares a rigorous mathematical model for assessing coverage and connectivity in wireless networks and it has been used in several recent researches (e.g. Khanjary et al., 2014; Liu et al., 2013). In this paper, we use Continuum Percolation to analytically compute the critical density for coverage and connectivity in fixed-orientation directional sensor networks.

* Corresponding author.
E-mail addresses: khanjary@srbiau.ac.ir (M. Khanjary), sabaei@aut.ac.ir (M. Sabaei), mmeybodi@aut.ac.ir (M. Reza Meybodi).

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1.1. Problem statement

Finding the minimum number of sensors required to achieve a certain degree of sensing coverage and network connectivity is one of the fundamental issues in design of sensor networks. This will be more important and complicated when we deal with directional sensor networks. As more and more directional sensors are continuously deployed, the size of covered areas increases and, at some instant, the situation suddenly changes from small fragmented covered areas to a single large covered area which spans the entire field. We call this sudden change in the sensing coverage of a field the *sensing-coverage phase transition* (SCPT). Likewise, the number of connected components increases when more and more directional sensors are continuously added to a sensor network that is originally disconnected. At some point, the situation abruptly changes from a disconnected network to connected network. We call this abrupt change in the network topology the *network-connectivity phase transition* (NCPT).

Because these phase transitions occur at a given density (called *critical density*) and study of such phase transitions is an important topic in the *percolation theory*, we are interested in finding the *critical density* for SCPT and NCPT and then finding *critical density* for both by using the *percolation theory*. Due to *percolation theory*, the *critical density* is infimum density that for densities above it SCPT and NCPT almost surely occur (Khanjary et al., 2014).

Based on orientation properties of sensor nodes, we classified directional sensor networks to three categories: (1) *Aligned-orientation directional sensor networks* (ALODSNs) in which the orientation of all sensor nodes is the same and fixed. (2) *Fixed-orientation directional sensor networks* (FIODSNs) in which orientation of nodes is distributed on $[0, 2\pi]$ independently and uniformly and is fixed. (3) *Adjustable-orientation directional sensor networks* (ADODSNs) in which the deployment is such as FIODSNs but the orientation of sensing sectors could be adjusted after deployment by using an algorithm. In Khanjary et al. (2014), we analytically proposed a general approach to calculate the *critical density* for sensing coverage and network connectivity in ALODSNs for different field-of-view angles between 0 and π by using continuum percolation and in this paper, we present an approach to calculate the *critical density* in FIODSNs.

1.2. Related works

1.2.1. Density of nodes in directional sensor networks

While most of researches in this subject focused on placement e.g. Morsly et al. (2012), Target tracking (e.g. Wang et al., 2009), scheduling (e.g. Mohamadi et al., 2014; Hooshmand et al., 2013) and k-angel coverage e.g. Tseng et al. (2012), there are a few researches on density of nodes in directional sensor networks.

Liu et al. (2011) first proposed a new notion of coverage, entitled localization-oriented coverage (L-coverage for short) by using Bayesian estimation theory and then analyzed the relationship between the density of camera sensors and the L-coverage probability under random deployment. Han et al. (2008) considered the problems of deploying a minimum number of directional sensors to form a connected network to cover either a set of point locations or the entire target sensing area which are NP-hard and then presented two approximation algorithms for them. Chen et al. (2008) proposed a weighted centralized greedy algorithm (WCGA) to assign a weight to each orientation of each sensor. The weight function added in the WCGA could be adjusted according to different density of sensor nodes in directional sensor networks. Then, each sensor will select its orientation which has highest weight.

Wang and Cao (2011) proposed a novel model called full-view coverage. An object is considered to be full-view covered if for any direction from 0 to 2π (object's facing direction), there is always a sensor such that the object is within the sensor's range and more importantly the sensor's viewing direction is sufficiently close to the object's facing direction. They also derived a sufficient condition on the sensor density needed for full-view coverage in a random uniform deployment.

1.2.2. Percolation theory in sensor networks

The concept of continuum percolation, originally due to Gilbert (1961), is to find the *critical density* of a Poisson point process at which an unbounded connected component almost surely appears so that the network can provide long-distance multihop communication. Since then, Gilbert's model has become the basis for studying continuum percolation in wireless networks (e.g. Glauche et al., 2003; Jiang and Bruck, 2005). Recently, *percolation theory* has been considered by researchers to be used to examine coverage and connectivity in sensor networks too (Ammari and Das, 2008, 2009) and (Xing and Wang, 2008; Liu et al., 2012, 2013; Liang et al., 2009; Yang and Qiao, 2008; Balister et al., 2009).

Ammari and Das (2008) considered the critical density required to prepare sensing coverage and network connectivity in sensor networks simultaneously by using continuum percolation in two-dimensional sensor networks. Then, they extended their research to three-dimensional sensor networks (Ammari and Das, 2009). Xing and Wang (2008) considered the proper time to redeployment of failed nodes to keep the network connected. They examined the time of first partition in network and found it must be between $\log(\log n)$ and $(\log n)^{1/p}$ where n is the network size and $\rho > 1$. Liu et al. (2012, 2013) considered exposure-path prevention. Exposure-path refers to the path in a sensor network that an intruder could traverse and not being detected by sensor nodes. They proposed a bond-percolation theory based scheme by mapping the exposure path problem into a bond percolation model. Using this model, they derived the *critical densities* for omnidirectional sensor networks and directional sensor networks (Liang et al., 2009). Yang and Qiao (2008) considered following problem: *given a randomly deployed sensor network where sensors are active with probability p, how many sensors are needed to achieve connected-k-coverage?* Connected-k-coverage requires the monitored region to be k-covered by a connected component of active sensors, which is less demanding than traditional k-coverage and connectivity in which all active sensors participate in both coverage and connectivity simultaneously. They investigated the theoretical foundations about connected-k-coverage by applying the *percolation theory* and derived the *critical density* for connected-k-coverage under different ratio between sensing and communication radius of sensors.

Also, Balister et al. (2009) introduced a new type of coverage called trap coverage that scales better with large deployment regions. A sensor network providing trap coverage guarantees that any moving object or phenomena can move at most a known displacement before to be detected by the network, for any trajectory and speed. Also, they proposed some polynomial-time algorithms to determine the level of trap coverage achieved once sensors are deployed on the ground.

The research of this paper is similar to research done by Ammari and Das (2008, 2009) for omnidirectional sensor networks. But we are interested to do such research when the sensor network consists of nodes with only directional sensing ability such as camera sensor networks and Doppler probes.

1.3. Contribution

The contributions of this paper are two folds:

1. In this paper, we consider the directional sensor networks in which sensor nodes have been deployed in the region of