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Procedia Computer Science 116 (2017) 548–555

Procedia Computer Science

www.elsevier.com/locate/procedia

2nd International Conference on Computer Science and Computational Intelligence 2017, ICCSCI 2017, 13-14 October 2017, Bali, Indonesia

# Critical Density in Adjustable-Orientation Directional Sensor Networks Using Continuum Percolation

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**Abstract**

In this paper, we consider adjustable-orientation directional sensor networks (ADODSNs) in which nodes are deployed based on Poisson Point Process and the orientation of sensor nodes is distributed between 0 and 2π independently and uniformly. Despite of other kinds of directional sensor networks, orientation of sensor nodes in ADODSNS could be adjusted after deployment by using an algorithm. We call this kind of sensor networks, adjustable-orientation directional sensor networks. We calculate the critical density of nodes for both sensing coverage and network connectivity in such networks using continuum percolation where field-of-view angles of sensors could be between 0 and π. Critical density is the infimum density of nodes to prepare barrier coverage. Also, extensive simulations have been conducted to represent the results. The findings of this research could be used for offline design of directional sensor networks and also its online algorithms such as scheduling, coverage and tracking.


Peer-review under responsibility of the scientific committee of the 2nd International Conference on Computer Science and Computational Intelligence 2017.

*Keywords:* Critical density, continuum percolation, sensing coverage, network connectivity, adjustable-orientation directional sensor networks.

## 1. Introduction

Sensing coverage is one of the main criterion of quality of service in wireless sensor networks. Moreover, network connectivity is a graph-based problem to help sensors to communicate each other and forward their data to the sink.

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Peer-review under responsibility of the scientific committee of the 2nd International Conference on Computer Science and Computational Intelligence 2017.
10.1016/j.procs.2017.10.054

Preparing both sensing coverage and network connectivity are crucial to sense the region of interest and send the gathered data to the sink. There are several reviews e.g. [3] on sensing coverage and network connectivity issues.

In the other hand, Percolation Theory has been considered recently as a mathematical model to investigate coverage in wireless networks. Because Percolation Theory investigate the behavior of connected clusters in random graphs, it has been used in wireless networks e.g. [4] and also in sensor networks too e.g. [6-9,16]. Due to Broadbent and Hammersley [17] percolation model gave birth as a model for disordered mediums. In general, percolation theory is divided to two categories: discrete percolation [18] and continuum percolation [19]. In discrete percolation the edges of the lattice could be close or open due to a probability $p$ and may have different tessellation such as square, triangle, honeycomb and we are interested in finding critical probability ($p_c$) in which percolation occurs. In contrast, in continuum percolation, the positions of the points are randomly distributed and we are interested in finding the critical density ($\lambda_c$) at which a large clump of objects first appears that spans the entire network.

Considering the orientation properties of sensor nodes, directional sensor networks could be classified to three categories: 1) Aligned-orientation directional sensor networks (ALODSNs) [9] in which the orientation of all sensor nodes is the same and fixed. 2) Fixed-orientation directional sensor networks (FIODSNs) [16] 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 like FIODSNs but the orientation of sensing sectors could be adjusted after deployment by using an algorithm. In [9,16], we analytically proposed a general approach to calculate the critical density for sensing coverage and network connectivity in ALODSNs and FIODSNs, respectively. In this paper, we present an analytical method to calculate the critical density of nodes for both sensing coverage phase transition (SCPT) and network connectivity phase transition (NCPT) in ADODSNs for all field-of-view angles between 0 and $\pi$ using continuum percolation. Based on percolation theory, the critical density is infimum density of nodes such that for densities above it sensing coverage and network connectivity almost surely occur.

The remainder of this paper is organized as follows: section 2 gives a review on related works in the literature, section 3 presents terminology of the paper, section 4 illustrates our approach to calculate the critical density for sensing coverage in ADODSNs, Section 5 discusses on integrated sensing coverage and network connectivity in ADODSNs, section 6 presents the simulation results and finally section 7 concludes the paper. [†]

## 2. Related works

Due to Gilbert [1], the main concept of continuum percolation is finding the critical density in a network of objects distributed based on a Poisson point process at which an unbound spanning component almost surely appears that spans the region. The Gilbert's model has been considered as the basis for studying continuum percolation in wireless networks e.g. [4] and also examining coverage and connectivity in sensor networks [6-9,10-11,15-16].

As the first research in sensor networks, Ammari et al. [10] considered the critical density for sensing coverage and network connectivity in sensor networks simultaneously. They used continuum percolation in two-dimensional sensor networks consist of homogenous sensor nodes with communication radius of $R$ and sensing radius $r$. Also, they extended their research for three-dimensional homogeneous sensor network [11].

Xing et al. [15] used continuum percolation to find the time when first partition would be occurred in network due to lack of power in sensor nodes and showed that it must be between $log\,(\log n)$ and $(log\ n\,)^{(1/p)}$ which $n$ is the network size and $\rho > 1$. The result provides a theoretical upper bound for time of redeployment. Liu et al. [7] considered exposure-path prevention in omnidirectional sensor networks. Exposure-path refers to the path that an intruder could traverse without being detected by sensor nodes. They mapped exposure path problem into a bond percolation model and derived the critical density for two-dimensional sensor networks. In their next research, they also studied the exposure-path prevention in directional sensor networks [20].

Yang et al. [2] considered minimum number of sensor nodes needed to prepare connected-k-coverage in a randomly-deployed sensor network where sensors are active with probability $p$. They applied the percolation theory to

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† This paper is the third part of a three-part research to find critical density in three different kinds of directional sensor networks which its first two parts has been published in [9] for ALODSNs and in [16] for FIODSNs. Therefore, there might be some similarities.