



Coordinate-free quantification of coverage in dynamic sensor networks[☆]

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ABSTRACT

We present a methodology for analyzing coverage properties in dynamic sensor networks. The dynamic sensor network under consideration is studied through a series of snapshots, and is represented by a sequence of simplicial complexes, built from the communication graph at each time point. A method from computational topology called zigzag persistent homology takes this sequence of simplicial complexes as input, and returns a ‘barcode’ containing the birth and death times of homological features in this sequence. We derive useful statistics from this output for analyzing time-varying coverage properties.

In addition, we propose a method which returns specific representative cycles for these homological features, at each point along the birth–death intervals. These representative cycles are then used to track coverage holes in the network, and obtain size estimates for individual holes at each time point. A weighted barcode, incorporating the size information, is then used as a visual and quantitative descriptor of the dynamic network coverage.

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1. Introduction

Wireless sensor networks have gained attention and popularity when technological advances allowed for the development of small, low-cost wireless sensors. These simple devices could be distributed over a region, with each sensor (or ‘node’) gathering data about its local environment for purposes of monitoring, detecting or reporting. In recent years, the study of wireless sensor networks has significantly increased, with research into methodologies for the different layers of the sensor network protocol stack (physical, data link, network, transport and application layers), each developing into their own sub-field. Areas of application include

military, industrial, and environmental monitoring and tracking. See [2,27] for surveys of the field.

One of the issues in sensor networks that quickly gained interest is the so-called ‘coverage problem’ [13]. Given a set of (typically homogeneous) sensors, each with the ability to sense some region of immediate proximity to it, one wishes to make statements about the sensing ability of the entire network, taken as a whole. An initial question is whether every point in a region of interest is covered by at least one sensor. As sensor networks developed, it was no longer realistic to assume a static network, and node mobility became a factor in network analysis and design. It became clear that mobility of nodes could be considered not only for initial deployment [23,12], but also to improve coverage over time [18]. Thus, the development of methods to study dynamic, or time-varying sensor networks has become increasingly important.

A number of methods for determining area coverage were developed, as well as methods for efficient node deployment to provide complete or optimal coverage, see [24] for a survey. Such methods require geometric information about the

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locations of the sensors, or their distances from each other, in addition to information about the geometry of the coverage area for each sensor. Methods from computational and stochastic geometry have been used to study the coverage properties of dynamic sensor networks when complete geometric information is available [22]. The coverage is described using statistics such as the proportion of uncovered area at each time point, or the proportion uncovered over a time interval (where a point is considered covered if it is covered at any time during the interval). These descriptors have been used to analyze and compare various mobility models for dynamic networks, to determine advantages and disadvantages of each, as well as optimal strategies for intruder detection [19].

It is often desirable to avoid assuming the availability of geometric information, such as global coordinates for the nodes, or distances between them. Instead, ‘coordinate-free’ methods compute network properties using only local, binary information about which nodes are within communication range of each other. De Silva and Ghrist [7] were the first to propose a rigorous method for determining coverage which did not require location or distance information, but employed tools from simplicial homology theory (see Section 2 for details). Such homological methods are able to give guarantees that a network is covered at a single time point, or over a time interval, using only coordinate-free data.

Other researchers have used coordinate-free data to study network coverage by detecting approximate boundaries of coverage holes in static networks. Some methods (such as in [15] or [17]) define interior nodes using specifically structured sub-graphs ('flowers' or '3MeSH rings'), while another method defines boundary nodes by using breaks in iso-contours formed by hop distance from a base node [9]. One method estimates the boundary by using a multi-step procedure built using the cuts in a shortest path tree which 'forks' around coverage holes [25]. All of these methods can obtain good experimental results, but are relatively dependent on the network having a high density, so the holes are large compared to the distances between neighboring sensors [14].

In this paper, we consider the study of coverage properties of sensor networks which are both coordinate-free and time-varying. Information from the network is available as a series of discrete-time snapshots, where each node returns a list of the other nodes that are within its local area. Using this, we compute the number of coverage holes at each time point, as well as information about estimated hole sizes, and how the holes persist over time. This information is summarized in a ‘barcode’ describing the birth and death times of homological features in the network over time, and we describe the relationship between these features and the coverage properties. The barcode is obtained by employing a method from the mathematical field of computational topology, called zigzag persistent homology [3,4]. We also propose an additional algorithm which returns specific cycles in the network characterizing the coverage holes over time, which aid in estimating the size of the holes.

The method we describe here is the only one currently available which can quantify the coverage dynamics in a coordinate-free network. We will also see that it correlates well with other coverage measures which utilize full geometric information. Further, the barcode includes information about how coverage holes form, merge, split and close in the

time-varying network, which is not available using existing methods (whether geometric information is included or not). In the past, homological methods have been able to give guarantees that a network is covered at a single time point, or over a time interval, while geometric methods have been used to obtain summary statistics which describe the time-varying nature of the network coverage. Here, we use homological, coordinate-free methods to obtain a descriptor of the dynamic network coverage.

As our primary contributions, we propose how the ‘barcode’ output from zigzag persistence can be used as a quantitative descriptor of time-varying coverage in a network, and moreover describe an algorithm we developed for choosing a specific geometrically relevant cycle for each coverage hole in the network at each time point. The utility of the barcode is illustrated by using it to quantify and compare coverage dynamics for different models of sensor mobility. Our novel representative cycles are used in conjunction with a hop distance-based method to obtain size estimates for the holes, and this information is incorporated back into the barcodes, giving a visual and quantitative summary of the dynamic network coverage. Further examples demonstrate the effectiveness of this descriptor for tracking small coverage holes appearing in dense networks, identifying expanding failure regions, and monitoring the maintenance of a protective barrier of mobile sensors around a guarded region.

The organization of this paper is as follows: In Section 2 we will first describe the basics of simplicial homology, and how it has been effectively used to give global coverage guarantees for both static and dynamic coordinate-free networks. In Section 3 we will outline our primary computational tool, zigzag persistent homology, and describe the additional types of coverage results it allows. Section 4 details the hop distance-based filtration, and its use in estimating hole sizes for a given simplicial complex. Section 5 gives our method for obtaining specific representative cycles, and how these cycles can be used with the hop distance filtration to enhance the barcode with estimated size information for each bar at each time point. This is followed by examples illustrating the utility of the method, and concluding remarks.

2. Preliminaries

The sensor network coverage model we use assumes homogeneous, isotropic sensors with sensing radius r , so that each sensor is at the center of its associated coverage region, which is a disk of radius r . This ‘Boolean disk coverage model’ is the most widely used sensor coverage model in the literature [24]. Throughout this paper, we will assume that the network consists of n sensors, indexed 1 through n . If sensor i is located at $\mathbf{x}_i \in \mathbb{R}^2$, then denote the disk of radius r centered at \mathbf{x}_i as $B(\mathbf{x}_i, r)$. Then the coverage region \mathcal{R} , for the entire network, is the union of all such disks:

$$\mathcal{R} = \bigcup_{i=1}^n B(\mathbf{x}_i, r) \quad (1)$$

To study the coverage holes appearing in \mathcal{R} two concepts are useful: the concept of *homology*, and that of representing a sensor network with a *simplicial complex*. Homology is a mathematical method which, intuitively, is used to define and categorize holes in spaces, (which are exactly the features

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