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Network connectivity assessment and improvement through relay node deployment

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ABSTRACT

In wireless ad hoc networks, maintaining network connectivity is very important as high level network functions all depend on it. However, how to measure network connectivity remains a fundamental challenge. For example, a network can have good overall k-connectivity and yet still have a communication bottleneck. In this paper, we address how to locate bottlenecks and relieve them. A new connectivity measure based on the Cheeger's Constant is used for bottleneck discovery, and a partition algorithm that divides the network at the bottleneck is developed. After the network is partitioned, we consider deploying a relay node to increase the conductance of the network across the partition. The relay node deployment problem is formulated as an integer linear program to maximize the number of connections between the two sides of the cut, and then a convex optimization algorithm is used to find the precise location of the relay node, which is within the convex hull defined by the radio transmission ranges of all the nodes that can connect to the relay node. We show that the relay node significantly relieves the bottleneck and improves network connectivity, which is manifested by several network connectivity metrics. The partition and relay node deployment algorithms are then extended to the case where multiple relay nodes are available. Multiway partition and multiple relay node deployment algorithms are presented. Simulation results show this approach effectively enhances network connectivity with a small number of relay nodes.

1. Introduction

Network connectivity is not only an important measure of robustness, but also a critical property pertaining to overall network performance. The successful operation of many upper layer network functions such as routing, scheduling, and QoS provisioning depends on it. Wireless links are more prone to variation and failure, and therefore providing robust wireless connectivity is more challenging than for wired networks.

Wireless network connectivity is a function of node positions, the environment, and the protocol. Without changing the environment and the protocol, network connectivity can be improved through relay node deployment, or node movement. To determine where to deploy a new node or move a node requires quantifying connectivity. Previous studies have proposed several different connectivity measures, including bisection connectivity [1], k-connectivity [2], and end-to-end

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message connectivity [3]. The Fiedler value has been used to measure the bisection connectivity of a network [4], which uses spectrum analysis to find the network partition. Although the spectral method can also be used to partition a graph based on the Fiedler vector, the partition is not directly computed to find the bottleneck of a network. The Fiedler value only provides an overall scalar network connectivity measure.

Often wireless network connectivity is governed by the transmission range. If the node distribution is uneven, there may be several densely connected clusters, and the links between the clusters are likely to carry much more communication load than the rest of the network, and may result in a bottleneck. Having a bottleneck is detrimental for the network performance since the high stress at the bottleneck will cause additional delay and compromise the overall network throughput. It is imperative that the bottleneck be relieved to facilitate message exchange. Previous studies have addressed how to improve wireless network connectivity for various types of wireless networks, including unmanned air vehicle networks (UAVs) [5], robot networks [6], infrastructure-based wireless networks [7], as well as mobile ad hoc networks [1]. However, previous studies are not directly targeted at bottlenecks in a connected network. They either address how to repair connectivity in a disconnected network, or to provide k-connectivity throughout the network. The former can only ensure the network is fully connected but cannot guarantee the network is bottleneck-free; the latter, although requiring more resources to satisfy, still cannot guarantee a bottleneck-free network.

In this paper, we propose to use a different measure for network connectivity based on the conductance of the network, or the Cheeger constant of the underlying graph [8]. The Cheeger constant directly measures how bottlenecked the graph is. The larger the Cheeger constant, the better-knit the graph is. We propose a network partition algorithm based on the Cheeger constant measure, and then propose a relay node deployment algorithm to improve network connectivity. The proposed method is effective and practical, in the sense that it directly finds the bottleneck area and relieves it by putting a relay node in this area. We first address how to find a single bottleneck and then deploy one relay node, and then we extend to multiway partition and multiple relay node deployment.

The rest of the paper is organized as follows. In Section 2, we briefly survey the previous related work. In Section 3, we provide details about two other closely related network connectivity measures for comparison purposes, and in Section 4 we introduce the Cheeger constant. In Section 5, we propose a linear programming-based model for Cheeger partition. In Section 6, we present an algorithm that computes the relay node location. Then we present the multiway partition in Section 7 and multiple relay node deployment in Section 8. We evaluate the algorithms in Section 9 including comparison to other methods. Section 10 concludes the paper and points out future research directions.

2. Related work

In this section, we briefly survey some related work in network connectivity measures and methods for improving network connectivity.

The most related connectivity measure is the Fiedler value. Similar to the Cheeger constant, the Fiedler value is a widely-used metric that measures how well-connected a graph is [9,10]. It is a global connectivity measure associated with the entire graph. The larger the Fiedler value, the better the overall connectivity. The Fiedler value and the corresponding Fiedler vector have been associated with graph bisection connectivity in [1]. We will show in simulation that the proposed method does a better job in bisection than the Fiedler value based method. Computation of the Fiedler value is brittle with respect to time varying connectivity, because without full global information the Fiedler value goes to zero (the network appears to be disconnected), even if only one node is dropped. The proposed method is more robust when only partial information is available.

Algebraic distance is another graph connectivity measure. It was proposed in [11] to measure the connectivity strength between a pair of vertices in a graph. It is a local connectivity measure associated with each pair of vertices in the graph. If two vertices share similar neighborhoods, then they have a small algebraic distance, which indicates the connectivity between the two vertices is strong. To our knowledge, this measure has not been used in a communication network application or been associated with network performance.

A commonly used metric in network applications is k-connectivity. The majority of work uses vertex-connectivity, which is used to indicate if the network has k node-disjoint routing paths. For network reliability analysis and fault tolerant design, vertex-connectivity plays an important role. Some works use edge-connectivity, which has direct association with network throughput, assuming each edge, corresponding to a cable line or a wired communication link, has a fixed capacity.

Network connectivity improvement may be achieved though relay node deployment. Fiedler value based algorithms aim to find the relay node location(s) so that the Fiedler value is increased [1,6], and k-connectivity based algorithms aim to find the relay node locations(s) so that the graph k-connectivity is satisfied while minimizing the total cost. There are various cost functions, such as the number of relay nodes [12,13], or the communication distance.

Most work in relay node deployment is based on k-connectivity, and the largest application of it is sensor networking. Liu et al. [14] studied how to find the minimum number of relay nodes and their locations such that: (1) each sensor node is guaranteed to communicate with one relay node, and (2) the whole network is fully connected by relay nodes under the constraint of connectivity. Han et al. [13] addressed the deployment of a minimum number of relay nodes to establish k-vertex-disjoint paths between every pair of sensor and/or relay nodes or only between every pair of sensor nodes. The former is the single-tiered relay node placement problem, and the latter is called the two-tiered relay node placement problem.