Ad Hoc Networks 25 (2015) 228–236

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Construction of higher spectral efficiency virtual backbone in wireless networks

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ARTICLE INFO

Article history:
Received 27 August 2013
Received in revised form 22 May 2014
Accepted 20 October 2014
Available online 29 October 2014

Keywords:
Wireless networks
Virtual backbone
Shortest path
Higher throughput
Spectral-efficiency

ABSTRACT

One promising solution to improve the efficiency of wireless networks is to control the number of nodes involved in multi-hop routing by employing virtual backbone. On the one hand, a virtual backbone becomes more efficient as its size is getting smaller. However, as the size of a virtual backbone is getting smaller, the throughput of the virtual backbone is degraded since the length of a routing path between a pair of nodes through the virtual backbone can be much longer than their hop distance in the original network. Due to the reason, several efforts are recently made to identify a virtual backbone including a shortest path between every pair of nodes in the original graph. In this paper, we investigate a new strategy to compute higher throughput virtual backbone in wireless networks. We employ a new information theoretic metric called *spectral-efficiency* by Chen et al. and propose a new virtual backbone computation algorithm in homogeneous wireless networks with some interesting theoretical analysis. Our simulation results indicate our algorithm produces a virtual backbone with higher spectral-efficiency than the existing alternatives. We also conduct another simulation using OMNet++ and show the virtual backbone produced by our algorithm has the highest throughput.

1. Introduction

Recently, the concept of virtual backbone has been introduced to improve the efficiency and performance of wireless networks. The main idea of this approach is to establish a connected subset of nodes in a wireless network such that any two nodes can communicate with each other through the nodes in the subset. In essence, this approach decreases the number of nodes involved in message routing and reduces the amount of signal collision and interference. Meanwhile, it is apparent that such benefits can be magnified as the size of the subset becomes smaller. In [3], Guha and Khuller formulated the problem of computing a smallest virtual backbone in a given network graph as the minimum *connected dominating set (CDS)* problem. Since the minimum CDS problem is NP-hard in various network graphs, many efforts are made to introduce approximation algorithms for the problem.

Over years, the network community has tried to introduce a new metric for better routing algorithms. Frequently, these algorithms are built on a link-layer level abstraction of network, which does not fully consider the impact of the physical layer. Therefore, those algorithms do not concern about the fundamental performance limits of wireless communication such as spectral-efficiency. However, spectral-efficiency is an important concept in wireless networks since higher spectral-efficiency means higher network throughput [1,2]. In [26], the authors showed that given a one-dimensional linear network, there exists an optimal number of hops, which is not necessarily the shortest hop, in terms of maximizing end-to-end spectral-efficiency. In

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http://dx.doi.org/10.1016/j.adhoc.2014.10.013
1570-8705/

[24], Chen et al. introduced a new metric to find a spectral-efficient routing path in multi-hop wireless networks and proposed spectral-efficient routing algorithms.

To the best of our knowledge, there have been five research papers concerning about the routing cost in the construction of virtual backbone [14,13,16,17], and all of them share the same motivation: the cost of routing over a virtual backbone computed by a minimum CDS algorithm can be high. This is because any two nodes which are very near to each other in the original network graph may need to communication with each other using a very long routing path through the virtual backbone, which will degrade the performance of the wireless network.

In this paper, we investigate how to improve the throughput of a virtual backbone in wireless networks. We observe that all of the existing CDS computation algorithms with routing cost consideration use the number of hops as the cost metric of a routing path. Inspired by Chen et al. work which showed a path with higher spectral-efficiency is with higher throughput than a shortest hop path, we propose a new virtual backbone computation algorithm incorporating their spectral-efficiency metric so that we can obtain a virtual backbone with higher throughput. The contributions of this paper are as follows: first, based on the spectral-efficiency metric in [24], we define the *maximum spectral-efficient connected dominating set (MSE-CDS)* problem whose goal is to compute the most spectral-efficient virtual backbone in homogenous wireless networks. We also show this problem is NP-hard. Second, we propose a new algorithm for MSE-CDS, namely *spectrum-efficient virtual backbone generater (SE-VBG)*. We show the correctness of our algorithm and provide the proofs of some interesting characteristics of the algorithm. Third, via simulation, we compare the average performance of our algorithm against the existing competitors. Our simulation results show SE-VBG produces a CDS with higher spectral-efficiency. Last, using a comprehensive simulator, OMNet++, we show the virtual backbone produced by our algorithm is with higher throughput than the existing competitors. As a result, *our algorithm outperforms the competitors in terms of throughput, a performance metric of real importance, instead of the other existing abstract performance metrics, the size of virtual backbone and the average hop distance*.

The rest of the paper is organized as follows: related work is given in Section 2. In Section 3, we provide some preliminaries. The formal definition of MSE-CDS is given in Section 4. The description of our algorithm SE-VBG and corresponding analysis are in Section 5. We present the simulation results and corresponding discussions in Section 6 and conclude this paper in Section 7.

2. Related works

Over many years, virtual backbone has been studied as a promising approach to improve the efficiency of wireless networks. Since the benefit of the virtual backbone can be augmented as its size becomes smaller, many efforts are made to find smaller size virtual backbone. It is well-known that the minimum CDS problem is NP-hard in unit disk graph (UDG), and thus many people focused on the design of approximation algorithm for this problem [3,11,12,4]. In most cases, a *dominating set (DS)* is identified and some more additional nodes whose number is bounded by a constant factor of the DS are added to make the nodes in the DS connected. Frequently, a *maximal independent set (MIS)* is used as an approximation of the minimum DS problem, which is also NP-hard. In [5], Wan et al. showed the size of an MIS is bound by $4 \cdot |opt_{MCDS}| + 1$, where $|opt_{MCDS}|$ is the size of an optimal CDS opt_{MCDS}, for the first time. Later, the bound is tightened by a series of attempts such as [6–10]. To the best of our knowledge, the most tight bound is in [9], which states the size of any MIS is bounded by $3.4306 \cdot |opt_{MCDS}| + 4.8185$.

One crucial performance issue in the virtual backbone based routing is that the virtual backbone may not include the shortest path between a pair of nodes. As a result, any two nodes which are only a few hops far in the original network may need to communicate through a number of intermediate virtual backbone nodes. Clearly, this can reduce the performance (i.e. throughput) of the wireless networks adopting virtual backbone. In [15], Kim et al. discussed the importance of routing cost in virtual backbone construction for the first time. They also studied a joint optimization problem of minimizing the size of CDS and the diameter of CDS, and proposed a centralized algorithm and a distributed algorithm which have a constant factor approximation ratio for each of the optimization goals. In [14], Ding et al. introduced a polynomial time exact algorithm to compute a minimum size CDS including every pair of shortest paths between each pair of nodes in a given general graph. In [13], Ding et al. proposed a $(1 - \ln 2) + 2 \ln \delta$-approximation algorithm for the minimum routing cost CDS problem, whose goal is to find a minimum size CDS of a given general graph including at least one shortest path between every pair of nodes in the graph. Later, Ding et al. also extended this result into a wireless networks with directional antennas [16]. In very recent report by Du et al., the problem of computing a minimum CDS including a path for each pair of nodes whose length is bound by a constant factor α of the shortest path length between the nodes in the original UDG is studied [17], in which the authors proposed a centralized algorithm and a distributed algorithm for the problem and prove that the size of an output of their algorithms is bounded by $148 \cdot |opt_{MCDS}| + 208$ and α is in Fact 7 in their algorithms.

Over many years, several metrics for routing algorithms in wireless networks have been proposed by both information theory community [19,27] and networking community [21–23]. In [24], Chen et al. pointed out the results from information theory community is too complicated to use in practice and the results from networking community mostly focus on hop distance, which does not fully consider the impact of the physical layer. Previously, the authors in [26,20] found that there is a path with an optimal number of hops, not necessarily the shortest path, in terms of maximizing end-to-end spectral-efficiency. Based on this result, Chen et al. considered the problem of computing a maximum spectrum-efficiency routing path in multi-hop wireless networks, with the constraint of equal bandwidth sharing, and proposed two efficient heuristics for sub-optimal solution. In [25], Sadd improved this result