Available online at www.sciencedirect.com
ScienceDirect
Computer Communications 29 (2006) 3092–3103
computer communications
www.elsevier.com/locate/comcom

An SPT-based topology control algorithm for wireless ad hoc networks

Szu-Chi Wang [a], David S.L. Wei [b], Sy-Yen Kuo [a,*]

[a] Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan
[b] Department of Computer and Information Sciences, Fordham University, Bronx, NY, USA

Available online 17 January 2006

Abstract

In this paper, we present a localized Shortest-Path-Tree (SPT) based algorithm that copes with the topology control problem in wireless ad hoc networks. Each mobile node determines its own transmission power based only on its local information. The proposed algorithm first constructs local SPTs from the initial graph, after which the total power consumption is further reduced by allowing each mobile node to search the replaceable links individually. The constructed topology ensures network connectivity, and possesses the following desirable energy-efficient features: (i) the power stretch factor is bounded and can be predetermined, (ii) the power consumption is evenly distributed among the mobile nodes, and (iii) the total power consumption is lower than that obtained by the best known algorithms. The performance improvements of the proposed algorithm are demonstrated through extensive simulations. We conclude our work with a discussion of future research directions toward more integrated mobile network architectures.

Keywords: Ad hoc networks; Energy efficiency; Localized algorithm; Topology control

1. Introduction

Wireless ad hoc networks have been proposed as an alternative to cellular networks for use in areas where the existing communication infrastructure has been disrupted or destroyed (e.g., due to an earthquake or flood), or where construction of a fixed infrastructure would be inconvenient or impossible (e.g., on a battlefield or in space). In such networks each node must serve as a user and as a router. A wireless link between any two nodes can be established if the radio transmission range of each node can cover the other. In the case of insufficient radio transmission range between the two nodes, multiple "hops" may be required, whereby intermediate nodes re-broadcast the messages until the destination node is reached. The reliance on wireless multi-hop communications to maintain connectivity among nodes adds new complexity to the design and operation of the network. Furthermore, the lack of a physical backbone poses a strong need for topology control of the network. It has been shown that the performance of a protocol for an ad hoc network can be enhanced if the protocol is based on overlaying a virtual infrastructure on the ad hoc network. Also, due to the finite power supply of a mobile node, power conservation has been widely used as a primary control parameter in the design of protocols for wireless ad hoc networks. Therefore, the problem of power-efficient topology control has attracted increasing attention from researchers in the area of wireless networking.

In this paper, we propose an algorithm for constructing an energy-efficient topology for wireless ad hoc networks. Such networks can be modeled by a weight directed graph $G = (V, E)$, where V represents the set of all mobile nodes and E represents the set of interconnections between the nodes. For each edge $(u, v) \in E$, node v must be in the transmission range of node u. We use $\|uv\|$ to denote the Euclidean distance between nodes u and v. The weight of the edge (u, v), denoted by $w(u, v)$, can be formulated as $t \cdot \|uv\|^{\alpha} + rp(u, v)$ in the most widely used power-attenuation model, where t is a threshold related to the signal-to-noise ratio

* Corresponding author.
E-mail address: sykuo@cc.ee.ntu.edu.tw (S.-Y. Kuo).

0140-3664/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.comcom.2005.11.006

at node u, and α is a constant between 2 and 5 depending on the wireless transmission environment. The first part of the equation is typically called the *transmitter power*, which is the power consumed by transmitting a signal from node u to node v. The remaining part is the power consumed by the receiver and is called the *receiver power*. We assume that all receivers have the same power threshold for signal detection, and the value of t is thus an appropriate constant. Hereafter, the sum of the transmitter power and the receiver power is called the *transmission power*. Also, throughout the paper, we use the terms link and edge interchangeably.

We assume that all mobile nodes are distributed on a two-dimensional plane and each mobile node has a GPS receiver that acquires information about the node's location. Initially, all mobile nodes are operated at full transmission power and have the transmission radius equal to one unit by a proper scaling. Consequently, the resulting graph G can be modeled as a unit-disc graph (denoted as $\mathrm{UDG}(V)$) and there is an edge between two nodes if and only if their Euclidean distance is at most one. We assume that $\mathrm{UDG}(V)$ is strongly connected. All the mobile nodes have unique identifiers (*ID*) numbered from 1 to N, where $N = |V|$. Each mobile node can individually adjust its own transmission power. We also assume that omni-directional antennas are used by all the mobile nodes to transmit and receive signals. Wireless ad hoc networks are power constrained; thus, it is undesirable to require each mobile node to always transmit at maximum power. Otherwise, the total power consumption would often be unnecessarily high and transmission interference would occur more frequently. In fact, it has been shown that mobile nodes expend most of their power in communications [1]. As a result, each mobile node should adjust its transmission radius to reduce its power consumption, while still maintaining network connectivity. Due to the infrastructureless nature of ad hoc networks, it is preferable that the network topology should be constructed in a localized manner to avoid flooding the network. Stojmenovic and Lin gave the definition of a localized algorithm in [2]. A distributed power control algorithm is called localized if each node can decide its transmission power based only on the information of the nodes reachable in a small constant number of hops.

In this paper, we adopt several definitions given in [3]. Let f be a complete transmission power assignment on V, and G_f be the associated communication graph. Clearly, $G_f \subseteq G$. The total power consumption of f (denoted by $tpc(f)$) is defined as $\sum_{u\in V} f(u)$, where $f(u)$ is the minimum transmission power needed to reach all the neighbors of u in G_f. A given path, $\prod(u,v)$, from node u to node v in G_f can be expressed as $\prod(u,v) = v_0v_1 \cdots v_{h-1}v_h$, where $u = v_0$, $v = v_h$. The length of the path $\prod(u,v)$ (denoted by $|\prod(u,v)|$) is h, and its transmission power is defined as

$$p\Big(\prod(u,v)\Big) = \sum_{i=1}^{h} w(v_{i-1}, v_i).$$

Given a communication graph H, the *minimum-energy path* between nodes u and v, denoted by $\prod_{\min}^{H}(u,v)$, is a path whose total power consumption is the minimum among all the paths that connect these two nodes in H. Let $p_H(u,v)$ denote $p(\prod_{\min}^{H}(u,v))$. The *power stretch factor* of the graph G_f with respect to G is then defined as

$$psf_{G_f}(G) = \max_{u,v\in V, u\neq v} (p_{G_f}(u,v)/p_G(u,v)).$$

In the literature, the two most widely used energy conservation approaches are: (i) reducing the transmission power of each node; and (ii) reducing the total power consumed by all nodes involved in one communication session. The latter can be achieved by preserving the minimum-energy paths of the given $\mathrm{UDG}(V)$. However, these two approaches may offset each other; a relevant discussion can be found in [4]. The major focus of our work is to develop a localized topology control algorithm in which each mobile node makes a decision about its transmission power based solely on its local information. As these locally made decisions collectively ensure global network connectivity, the network topology controlled by each node's transmission power must be energy-efficient. More specifically, the proposed algorithm must achieve the following objectives: (i) it must be capable of adjusting the transmission radii of the nodes with low total power consumption; and (ii) it must have a constant bounded power stretch factor. Fig. 1 illustrates that the strongly connected property could be preserved under the reduction of transmission radii and the excision of links. Moreover, we consider several practical issues, particularly the integration of ad hoc networks into IP-enabled services. IPv6 is designed to satisfy various future networking requirements and a more advanced support of mobility can be achieved accordingly. Therefore, we examine relevant studies and identify some practical challenges that will be important in next-generation networks.

The remainder of this paper is organized as follows. Section 2 briefly introduces related works. Section 3 describes the basic concepts and properties of our algorithm. In Section 4, the superiority of our algorithm is demonstrated via simulations. Also, using several important metrics, we compare the energy-efficiency of our topology with that of other algorithms. In Section 5, we propose an efficient distribution method to deal with node mobility. Finally, in Section 6, we present our conclusions and indicate some future research directions.

2. Related works

In [5], Rodoplu and Meng described a distributed protocol for constructing a topology that guarantees the preservation of the minimum-energy path between every pair of nodes connected on the original graph G. The concept of relay region was first introduced in their paper. Recently, based on the results in [5], Li and Halpern [6] proposed a