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On channel-discontinuity-constraint routing in wireless networks ☆

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ABSTRACT

Multi-channel wireless networks are increasingly deployed as infrastructure networks, e.g. in metro areas. Network nodes frequently employ directional antennas to improve spatial throughput. In such networks, between two nodes, it is of interest to compute a path with a channel assignment for the links such that the path and link bandwidths are the same. This is achieved when any two consecutive links are assigned different channels, termed as "Channel-Discontinuity-Constraint" (CDC). CDC-paths are also useful in ***TDMA*** systems, where, preferably, consecutive links are assigned different time-slots.

In the first part of this paper, we develop a t-spanner for CDC-paths using spatial properties; a sub-network containing $O(n/\theta)$ links, for any $\theta > 0$, such that CDC-paths increase in cost by at most a factor $t = (1 - 2\sin(\theta/2))^{-2}$. We propose a novel distributed algorithm to compute the spanner using an expected number of $O(n \log n)$ fixed-size messages.

In the second part, we present a distributed algorithm to find minimum-cost CDC-paths between two nodes using $O(n^2)$ fixed-size messages, by developing an extension of Edmonds' algorithm for minimum-cost perfect matching. In a centralized implementation, our algorithm runs in $O(n^2)$ time improving the previous best algorithm which requires $O(n^3)$ running time. Moreover, this running time improves to $O(n/\theta)$ when used in conjunction with the spanner developed.

1. Introduction

Wireless infrastructure networks (WINs) are gaining prominence as they are being increasingly deployed in metro areas to provide ubiquitous information access [2]. WINs provide a low-cost scalable network, support broadband data, and allow use of unlicensed spectrum. WINs have a wide area of applications, including public internet access [2], PORTAL [3], video streaming [4], and underground mining [5]. In order to increase the bandwidth in the WINs, nodes employ multiple wireless transceivers (interface cards) to achieve simultaneous transmission/reception over multiple orthogonal channels.

Recent research has focused on effectively harvesting the available bandwidth in a wireless network. Wireless interference is the key factor that limits the achievable throughput. The interference is encountered in two ways: (1) a node may not receive from two different nodes on the same channel at any given time; and (2) a node may not receive and transmit on the same channel at any given time. Moreover, if omnidirectional antennas are employed, then there may be at most one node transmitting on a channel in the vicinity of a node that is receiving on that channel. In a wireless network, a flow is defined as packets transmitted along a single path between a source–destination pair. At any given time, multiple flows may be present in the network. Hence, the interference constraints in wireless networks may be divided into two categories [6]: *inter-flow* and *intra-flow*. The inter-flow interference

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refers to the scenario where two links belonging to two different flows cannot be active (on the same channel) at the same time as one receiver will experience interference due to the other transmission. The intra-flow interference refers to the scenario where two links belonging to the same flow cannot be active (on the same channel) at the same time. The same problem arises also in the TDMA setting, where a node can be used for streaming applications, but has to receive and transmit messages in different time slots.

The problem of routing and channel assignment in WINs refers to computing paths and channel assignment on the paths such that there is no inter-flow and intra-flow interference. If the bandwidth of a link is B, then the end-to-end throughput on the path is also B as all the links in the path can be active simultaneously. The problem of *joint routing and channel assignment* is challenging when nodes employ omnidirectional antennas and hence, it is typically solved as two independent sub-problems. For a given set of calls where the routing is known, the problem of channel assignment may be mapped to the *distance-2 vertex and edge coloring* problems [7]. The distance-2 coloring problems refer to coloring the edges or vertices such that two edges or vertices which are two hops or less from each other cannot have the same color. Thus, the objective is to compute a channel assignment, i.e., coloring of the edges satisfying the limit on the number of transceivers at each node. Distance-2 vertex and edge coloring problems are well known NP-hard problems and hence, the problem of channel assignment for networks employing omnidirectional antennas is challenging. Various approximation algorithms and heuristics have been developed for distance-2 coloring with different objectives, such as minimizing interference, maximizing throughput, and minimizing the number of required channels with combinations of these objectives [8–14]. In [15], the authors develop an approach based on balanced incomplete block design to assign channels such that the communication network is 2-edge-connected with minimum interference. In [16], a heuristic based on random channel assignment policy is developed to maintain connectivity of the network.

Among the works that compute paths for multi-channel networks, [17,18] take into account factors such as link loss rate, link data rate, channel diversity and, in the latter work, inter-flow interference in developing a new metric to be used in a routing protocol to find efficient paths with low interference.

When considering static traffic, [19,20] propose a complete system which handles routing and channel assignment separately. They aim to maximize throughput and do not provide any theoretical bounds on the performance of their system. [21–23] provide centralized and distributed schemes to provide routing and channel assignment in order to maximize throughput in the network for a given static traffic with guarantees on the performance. Again, these works handle routing and channel assignment separately and this leads to sub-optimal results. Finally, [24] considers the objective of achieving a given data rate under a simplified model of interference and provides approximation guarantees.

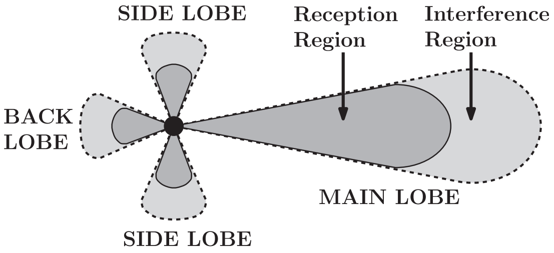

Fig. 1. Beam patterns of directional antennas. Signal is reinforced in the main lobe and transmitted weakly in the side and back lobes. The darker regions represent regions of reception and nodes in the lighter regions experience interference.

It has been shown in [25–27] that the capacity of WINs may be further improved by increasing spatial reuse by employing directional antennas. See Fig. 1 for an illustration of the transmission range of directional antennas. The problem of channel assignment in networks employing directional antennas may be mapped to the edge-coloring problem [28]. In [29], a network architecture with nodes employing non-steerable directional antennas is developed. The authors develop approaches for routing and channel assignment by considering tree-based topologies rooted at “gateway” nodes.

There are indications that the problem of finding a route and channel assignment for the links along the route such that all links can be active simultaneously is NP-complete when the nodes employ omnidirectional antennas. Our algorithms are designed for the frequent cases for which the effect of interference between independent links can be minimized. This is due to the fact that because of increased spatial reuse and with good network planning regarding node placement and beam direction/width, the effects of both inter-flow interference and intra-flow interference between independent links is mitigated. The possibility of employing careful planning in deploying wireless networks using directional antennas is clearly increasing as their prices and accuracy are rapidly improving.

1.1. Topology control

A fundamental technique used to speed up network operations is the use of spanners to perform topology control. These are subnetworks which make use of the spatial properties of the network in order to make the network operations more efficient. We call a subnetwork of the network a t-spanner if it maintains connectivity of the network and, the route between any two arbitrary nodes is longer than the original shortest route by a factor of at most t. There has been extensive research on spanners in the general setting (see [30–33]). These works do not consider the interference constraints explicitly but instead try to achieve other properties such as planarity or bounded degree. In the case of networks employing directional antennas, it is interesting to consider the approach of controlling the width and orientation of the directional antennas. Such methods would aid in network planning to satisfy various criteria (e.g., guaranteeing the existence of high throughput paths while making the process of finding routes more efficient). Some related works are [34], in