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Novel scheduling algorithms for concurrent transmit/receive wireless mesh networks

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ABSTRACT

Recently, in an effort to increase the capacity of Wireless Mesh Networks (WMNs), researchers have begun equipping routers with multiple interfaces/radios, and connecting each one to a directional or smart antenna. A key feature of these routers is their ability to transmit or receive from multiple neighbors simultaneously. Hence, they have orders of magnitude higher capacity than their omni-directional counterparts. This significant capacity increase, however, is predicated upon a link scheduling algorithm that maximizes the number of active links at any given point in time. This paper proposes a number of link activation algorithms that derive maximal bipartite graphs from general topologies. These algorithms provide different trade-offs in terms of computation time and optimality. A key highlight is a greedy algorithm that has a time complexity of $O(|V|^2)$, where V is the set of routers. Apart from that, we outline two algorithms that use an approximation to the well known maximum cut problem, and also a brute force algorithm, which is capable of deriving an optimal link activation schedule. The output from our algorithms can then be used by a spatial Time Division Multiple Access (TDMA) Medium Access Control (MAC) protocol to schedule concurrent transmitting and receiving links. We have verified our algorithms on various topologies with increasing node degrees as well as node numbers. From extensive simulation studies, we find that our algorithms have good performance in terms of number of links activated, superframe length, and end-to-end packet delay.

1. Introduction

Wireless Mesh Networks (WMNs) have many applications. Some examples include providing broadband access to rural villages in developing countries [22], interconnecting consumer devices in Wireless Personal Area Networks (WPANs) [5], traffic control [15], and smart grids [26]. These applications are enabled by the self-organizing and self-configuring characteristics of WMNs as well as the ubiquity of wireless devices. In particular, IEEE 802.11 access points (APs) are now a commodity that can be used to set up low cost WMNs that have good reliability and low maintenance [1].

The success of WMNs, however, hinges on their capacity to support bandwidth intensive, multi-media applications. Unfortunately, the seminal paper by Gupta and kumar [13] states that the throughput of each node decreases to zero when the number of nodes increases. This theoretical result has been validated via simulation by Das et al. [9] and Li et al. [16], where they found the throughput achieved by nodes are in the order of kilobits per second even though nodes are equipped with radios that are capable of operating at several megabits per second.

To date, researchers have devised various solutions to increase the capacity of WMNs. A promising approach is to equip routers with smart or directional antennas [22,24,3,12,17]. These antennas give a router the ability to

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focus its transmission energy or electromagnetic beam on a given geographical region, and effectively lowers the noise floor of nearby routers. In other words, routers experience higher gains during reception and thus lower Bit Error Rates (BERs). More importantly, directional antennas increase spatial reuse significantly as routers are able to transmit simultaneously. For example, Yi et al. [28] showed that for random networks with both transmitter and receiver using a directional antenna, the order of improvement in throughput is $\frac{4\pi^2}{\alpha\beta}$, where α and β are the beamwidth of the transmitter and receiver's directional antenna respectively. In contrast, if nodes use omni-directional antenna, for a given node density n, the total end-to-end capacity is approximately $O\left(\frac{n}{\sqrt{n}}\right)$, and the available throughput of each node is $O\left(\frac{1}{\sqrt{n}}\right)$.

In this paper, we consider routers that are capable of forming multiple links simultaneously to their neighbors. This is an important distinction to existing works on directional or smart antennas that seek to maximize spatial reuse by increasing the number of transmitting node pairs. Our work, on the other hand, considers maximizing the number of links established by the said routers with their respective neighbors as opposed to only a *single* point-to-point directional link. In other words, we maximize the number of packets transmitted or received by each router, with the constraint that routers can only transmit *or* receive simultaneously. This, however, requires a link scheduler that activates links in a way that maximizes network capacity. Specifically, it finds the maximum number of links that can be activated in each time slot. Moreover, it must ensure that all links are serviced at least once within a superframe. Note that maximizing the number of active links in each time slot indirectly minimizes the superframe length, which in turn reduces the end-to-end delay of packet transmission.

We transform the link scheduling problem into finding a set of MAX-CUTs, i.e., a set of maximal bipartite graphs, which in turn are used to determine whether a router is transmitting or receiving on all its interfaces in a given time slot. In addition, we employ two optimizations to opportunistically activate links that have been serviced in prior slots to boost network capacity. Since generating MAX-CUT is NP-complete [27], we propose to use Goemans–Williamson's algorithm (GWA) [11] and Vazirani's approximation [27], the most effective approximation and a computationally efficient greedy algorithm, respectively, to generate each MAX-CUT. In addition, we propose a novel, fast, greedy algorithm, described in Section 6, that recursively creates maximal bipartite graphs. From our extensive simulation studies involving topologies with increasing node degrees and densities, we found the link schedule generated by our greedy algorithm to have comparable performance to those that use brute force or GWA, but with orders of magnitude faster computation time. In a nutshell, this paper makes the following contributions:

- A novel greedy scheduler with a time complexity of $O(|V|^2)$, where V is the set of nodes/routers. Moreover, unlike existing approaches (e.g., [22]), it works on general graphs/topologies. This is critical as it gives network operators the flexibility to focus on coverage instead of being limited by topology constraints.
- Three link schedulers that build on the following algorithms: (i) Goemans–Williamson's algorithm (GWA) [11], which produces the best approximation to the well known maximum cut problem, (ii) Vazirani [27], a randomized bipartite graph construction algorithm, and (iii) brute force, which exhaustively derives the maximum bipartite graph from a given topology. From extensive simulation studies, we find that our greedy algorithm generates at most 5–8% fewer links when compared to the more computationally intensive approaches in (i) and (iii), and consistently outperforms that in (ii). Interestingly, for general graphs, our greedy algorithm yields a slightly shorter superframe length than the GWA-based approach.
- An outline for two optimizations that yield up to 44% improvement in network capacity. Specifically, these optimizations ensure the capacity of each slot is maximized, and provide links with additional service in the same superframe. In addition, these optimizations also help boost the aforementioned approaches by the same percentage.

Next, in Section 2, we show how routers are able to concurrently transmit (Tx) or receive (Rx) packets in WMNs. Then in Section 3, we define the scheduling problem before presenting related works in Section 4. We then outline our approaches that use graph coloring and MAX-CUT approximation algorithms in Section 5. Given the high computation time of these algorithms, we propose a greedy scheduler in Section 6, and illustrate how it works using an example. After that, in Section 7, we prove several properties concerning our scheduler. Section 8 first presents our research methodology, followed by our results from our investigation on topologies with varying node degrees and densities. Our conclusion and future work are presented in Section 9.

2. System architecture

Our scheduler applies to WMNs that comprise of routers capable of concurrently transmitting *or* receiving packets from multiple neighbors. We first present two example architectures of such WMNs before outlining a Medium Access Control (MAC), called 2P, that uses the schedule produced by our algorithm to activate links concurrently in each time slot.

Raman and Chebrolu [22] used off-the-shelf IEEE 802.11 access points (APs) along with high gain directional antennas to interconnect rural villages in India. Routers have multiple radios, each connected to a parabolic grid antenna. Raman and Chebrolu also adjusted their transmission power, and disabled immediate acknowledgment and carrier sense. These changes help reduce the impact of sidelobes which otherwise would have prevented interfaces on a router from initiating transmission or reception. Note that, unlike in our paper – all links reside on the same channel – Raman and Chebrolu have exploited multiple