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Fair flow rate optimization by effective placement of directional antennas in wireless mesh networks

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HIGHLIGHTS

- This is the first work to jointly optimize antenna placement, link scheduling, rate adaptation and routing for fair flow optimization in WMNs.
- Mixed integer programming models for preset and non-preset routing are formulated.
- Both the exact method branch-and-price and two heuristics are provided.
- Some analyses are done for the optimization model and extensive experiments are conducted to find some interesting results.

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ABSTRACT

Directional antennas have been used to solve interference and connectivity issues in wireless networks for some time. Many scenarios have been presented and often positive conclusions are drawn, i.e., showing the increase in capacity. However, to date the research has mainly focused on either antenna placement or transmission scheduling but not the two combined. Such consideration will become increasingly important with the advent of heterogeneous networks and other possible combinations of public access networks in the near future.

In this paper we study the problem of maximizing the minimal flow rate from gateways to mesh routers in wireless mesh networks using a combination of directional and omnidirectional antennas. We present mixed integer programming models for deploying directional antennas at appropriate nodes, and finding a corresponding transmission scheduling (with data rate adaptation) for non-preset and preset routing. By introducing directional antennas, the considered traffic objective is substantially improved, which is verified by the numerical study. Interestingly, the results also show that it is not always optimal to deploy directional antennas at all possible nodes due to the increased interference observed at non-receiving nodes within the beam width.

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1. Introduction

The Wireless Mesh Network (WMN) has been thought to be a promising architecture for numerous applications such as indoor broadband connection, public access networks and extensions to cellular networks, see for example [1,2]. As multi-hop networks, WMNs face the unfairness problem that clients near mesh gateways tend to get more traffic than clients

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further away. From a traffic engineering standpoint, a key problem is how to maximize the minimal flow rate from gateways to mesh routers (the main traffic in WMNs). This can be achieved by the max–min fairness which is well fit for WMNs, since resources can be fairly allocated without being aware of traffic loads and patterns.

Although some work has been done in WMNs considering fairness and related resource allocation [3,4], the benefits of using directional antennas to improve the fairness has not been fully studied. In many deployment scenarios WMNs will operate in highly dense networks where interference from the WMN nodes themselves as well as external nodes may cause degradation of the performance. To overcome or minimize the negative effects of this interference, the use of directional antennas has been proposed [5], by focusing transmission energy between communicating pairs of nodes, resulting in increased spatial reuse and transmission range compared with omnidirectional (omni) antennas.

In this paper we study the problem of maximizing the minimal flow rate between gateways and routers when omni and directional antennas are used alternatively. Without loss of generality, we consider using a single channel since this model can be easily extended to the case of multiple channels. We present a solution for maximizing the minimal flow rate by jointly optimizing directional antenna placement, transmission scheduling and link rate adaptation for preset and non-preset routing. An advantage for considering the preset routing is that the developed model can be applied in WMNs without altering the used routing protocol. For example, for IEEE 802.11s-based WMNs, the default routing protocol specified in this standard, i.e., Hybrid Wireless Mesh Protocol [6], can be retained. The link scheduling scheme resulted from this model can be directly used. However, in some scenarios where designing a high-performance WMN is the main concern, optimizing routing will be worth to be investigated, although this may increase the implementation complexity. Moreover, from the theoretical point of view, it is also valuable to know the performance bound achieved by optimizing the routing, which will provide guidelines for engineers to balance between the performance and the implementation complexity.

The link transmission scheduling is designed based on a Time Division Multiple Access (TDMA) variant, i.e., the total time is divided into several time slots, where a group of active links satisfying the signal-to-interference-plus-noise-ratio (SINR) constraint is selected for each time slot. Note that the SINR depends on the type of antenna installed on the nodes and we therefore derive an antenna-aware SINR constraint for transmission scheduling. The data rate of each active link is controlled by selecting different modulation and coding schemes (MCSs). We incorporate routing in the model in two different ways. One way is to establish routing in advance and the optimization model is built on the determined topology. The other way is to optimize the routing by solving the optimization model. Besides, the number of available directional antennas is also limited by a constant due to the budget.

Combining all the elements described above together, we develop general mixed integer programming (MIP) models to maximize the minimal flow rate. The MIP model is decomposed as a master problem and a pricing problem, and solved exactly by the branch-and-price method. By solving the model, we are able to determine the number of directional antennas needed to achieve the desired performance and also locations where these directional antennas should be deployed. An example of optimal solution is illustrated in the numerical study and the variation of the max–min flow with the beam width and the number of available directional antennas are also investigated. We also provide two heuristics as complementary methods to solve the problem. The comparison of the heuristics with the exact method is shown in the numerical study.

To the best of our knowledge, ours is the first work to jointly optimize link scheduling, link rate control, routing and antenna deployment for fair flow optimization. The obtained centralized solution yields theoretical performance bounds and therefore represents a useful component for comparing against future solutions aiming at achieving the same optimization goal in a distributed manner.

The paper is organized as follows. Section 2 summarizes related work and explains our motivation for conducting this work. Section 3 introduces the adopted antenna model and describes the basic concepts and notations which will be used in the optimization model in Section 4. The exact method and the heuristic methods for solving the problem is presented in Section 5. Section 6 extends the optimization model in Section 4 by taking into account the routing. Section 7 presents extensive numerical studies for performance evaluation and comparisons. Finally, Section 8 concludes the paper.

2. Related work

The fairness problem has been extensively studied in WMNs and a large body of works can be found, see a survey in [3] and references therein. Among all fairness criteria, the max–min fairness was widely studied. The authors in [7] studied the end-to-end bandwidth allocation problem in WMNs with cognitive radios. The bandwidth allocation problem refers to that each node is allocated with certain bandwidth for communicating with gateways. Two objectives are considered in this paper, including simple max–min fairness (maximizing the minimal bandwidth) and lexicographical max–min fairness. The paper [8] studied the max–min fairness problem in WiMAX mesh networks under two assumptions, i.e., assuming that each link has the same transmission capacity and assuming that different links have different transmission capacity. The bandwidths are firstly distributed in the manner of max–min fairness among all traffic flows, and then resources are allocated afterwards. The paper [9] established a log-convex rate region for a large class of IEEE 802.11 mesh networks, and proposes lightweight methods for achieving max–min fairness. The paper [10] presented different mixed integer programming models for joint routing, transmission scheduling and rate selection under max–min flow fairness in wireless mesh networks. Both exact and heuristic methods are developed to solve the proposed models. There are also some work studying the max–min fairness in WMNs by conducting experiments in simulators for performance evaluation. For example, the

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