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Joint link rate allocation, routing and channel assignment in multi-rate multi-channel wireless networks

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ABSTRACT

In this paper we address the issue of joint routing, channel assignment, scheduling and link rate allocation in multi-rate multi-channel wireless networks with the goal of increasing network capacity. Many wireless standards support a variety of modulation and coding schemes, which allow devices to choose from several transmission rates. Typically, the highest possible rate is used for transmission, but the potential for increased spatial reuse and capacity exists when using lower rates due to higher interference tolerance. This problem of selecting link rates is further complicated in a multi-channel network. Channel assignment affects the sets of interfering links, and as such also influences the optimal choice of link rates. And there is also an interdependency between routing and both rate and channel assignment. In this work we analyze the joint problem and, due to its hardness, propose a fast heuristic algorithm (JMR) to solve it. We evaluate this algorithm through numerical experiments in a wide variety of configurations, showing that potential for improved capacity via link rate allocation depends on a variety of factors which relate to the capability and need of exploiting spatial reuse, and which include the transmission power, the number of channels and the network architecture and topology. In this work we also propose an architecture for wireless mesh networks with increased capacity and under which optimized rate allocation is shown to notably increase performance. Finally, we evaluate the solutions found by JMR under the *ns-3* simulator using the 802.11a protocol stack, where it is shown that physical and MAC layer limitations reduce the performance gain of JMR.

1. Introduction and motivation

Wireless networks have gained tremendous popularity in the past 15 years. Recently there has been an explosion of wireless devices, and traffic has grown 20,000% in the last five years [1]. This is due to many factors, including the availability of high speed networks, more powerful mobile devices (smartphones, tablets), new applications and networks. The number of wireless devices and traffic is expected to keep growing rapidly in the next years [2], imposing the need for greater capacity and throughput.

Wireless networks are complex systems, owing to the multi-access nature of communications, presence of interference and time-varying characteristics of the wireless channel. This generates interdependencies across devices and network layers which demand the use of cross-layer design and optimization if we want to maximize their capacity [3,4].

In this paper we consider wireless networks where nodes are equipped with multiple radios and have several

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orthogonal frequency channels available for transmission. In addition, the radio interfaces have multiple modulation and coding schemes at their disposal, which allow them to transmit using one of several link rates. For example, the 802.11a standard supports eight different data rates (from 6 to 54 Mbps). There are several design choices that can be made in this system, including what frequency channel to transmit on (*channel allocation* problem), which of several link rates to use for transmission (*link rate allocation* problem), link *scheduling* and *routing*.

In this paper we study the joint link-rate allocation (LRA), channel allocation (CA), scheduling and routing problem. There is a well-known interdependency between routing and CA which requires a joint optimization of both to maximize throughput [5]. In addition, in this paper we show that there is also interdependency between routing, CA and LRA, meaning that a joint optimization of these problems is desirable to maximize performance. Although subsets of the problem have been extensively studied in the past, this joint problem has not. In many cases, LRA is ignored, assuming that all links transmit at the same rate or that the rates are fixed, or it is studied in a simplified context (e.g. single channel networks). One of the main topics of this paper is the subject of LRA in a complex multi-radio multi-channel wireless environment. To the best of our knowledge, this is the first work to consider LRA together with routing and CA.

In this paper we argue that LRA is a useful tool for improving spatial reuse. *Spatial reuse* refers to the capability of having concurrent transmissions on the same channel in the network [6], increasing area spectral efficiency and network capacity. A common way of exploiting spatial reuse is by separating concurrent transmissions in space, thus avoiding interference.

Most existing rate control or rate allocation methods only seek to transmit at a link's maximum possible rate. In this paper we study how with careful LRA, spatial reuse can improve and network capacity can actually be increased by transmitting at lower bit rates. Higher link rate increases link spectral efficiency (in (bit/s)/Hz), but it also requires higher SNR and makes links more sensitive to interference, requiring more links to transmit at different times and consequently reducing area spectral efficiency (in (bit/s)/Hz per unit area). In a general sense, optimal LRA is not just a question of transmitting at the highest possible rate, although that may be a good strategy in some scenarios.

We will see that allocating link rates to maximize network capacity is not trivial and depends on numerous factors at multiple layers of the system, such as network architecture/topology, number of channels, transmit power, medium access protocol, physical transceiver design, and even routing and traffic patterns.

In this paper we study the joint problem and propose an algorithm, called the Joint Multi-rate (JMR) to solve it. We focus on wireless mesh (multi-hop) topologies for the purpose of evaluating our solutions and studying the effects of LRA in multi-radio multi-channel environments, but the results and insight offered are not restricted to these networks. We have solved the problem on a variety of different topologies and system configurations, and in general, have observed that notable capacity gains can be achieved through optimized LRA, but these gains will depend on the numerous factors described above and will in many cases require cross-layer design to achieve them in real systems.

We also propose an architecture to increase the capacity of a Wireless Mesh Network (WMN) without the need to introduce more gateways. This is particularly useful when introducing more gateways is prohibitive for whatever reason (e.g. hardware costs or difficulty of extending the wired infrastructure). More importantly, we will see that optimal LRA notably increases capacity under this architecture.

The major contributions of this paper are:

- We model the joint routing, scheduling, LRA and CA problem, and propose a heuristic algorithm (JMR) to solve it.
- We do a comprehensive study of the joint problem, focusing on the effect of LRA together with routing, CA and other system parameters such as transmit power and number of radio interfaces. We evaluate capacity limits of LRA via numerical experiments on a wide number of configurations and system parameters.
- Study practical limitations of 802.11 hardware and Carrier Sense Multiple Access (CSMA) protocol in maximizing spatial reuse/area spectral efficiency, and its effect on optimal LRA. Extensive simulations in *ns-3* using 802.11a corroborate these limitations. We show that the success of JMR ultimately depends of the capability of the underlying hardware and protocols of exploiting spatial reuse.
- We propose a new architecture for WMNs, called the *ringnode* architecture, that achieves greater capacity than the basic architecture, and study the effects of optimized LRA in ringnode topologies, noting important differences with respect to standard topologies.

The rest of the paper is organized as follows. Section 2 reviews related work. In Section 3 we describe the two types of WMN architecture studied in this paper. Section 4 defines and formulates the joint problem. Section 5 describes the proposed JMR algorithm to solve the joint problem. In Section 6 we present numerical results of JMR. Section 7 analyzes the limitations of 802.11 regarding spatial reuse and how they will affect JMR, while Section 8 presents simulation results in *ns-3* under a 802.11a network. Finally, Section 9 concludes the paper.

2. Related work

The rate control method present in 802.11 hardware has the goal of adaptively selecting the highest rate for each link that achieves acceptable link quality, and thus ignores the issue of spatial reuse. Most of the works which in the past have studied rate control have essentially pursued the goal of improving this or similar mechanism. Examples include [7–10].

In [8], Choi et al. propose techniques to improve the performance of rate control in 802.11 networks, allowing nodes to distinguish between channel errors and collisions, so as to adapt only to channel errors. Kim et al. propose a routing metric in [9] for joint selection of routes and link