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# A group-based channel assignment protocol for rate separation in IEEE 802.11-based multi-radio multi-rate ad hoc networks

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ABSTRACT

Today's IEEE 802.11 devices support multiple channels and data rates. Utilizing multiple channels and data rates can increase the performance of IEEE 802.11 networks. However, the multi-channel design to exploit available channels is one of the challenging issues. Moreover, *performance anomaly* occurs in IEEE 802.11 multi-rate networks when high-rate and low-rate links share a common channel, which degrades the overall network capacity significantly. In this paper, we introduce an extension of conflict graph, called rate conflict graph (RCG), to understand the performance anomaly problem in IEEE 802.11 multi-rate networks. Then, we propose a group-based channel assignment (GCA) protocol for IEEE 802.11-based multi-radio multi-rate single-hop ad hoc networks. In GCA, each node is equipped with multiple IEEE 802.11 interfaces, and links are subdivided into multiple groups, called *component groups*, by obeying the interface constraints. Then, GCA utilizes RCG and a heuristic algorithm to separate different data rate links via multiple channels so that the performance anomaly problem is addressed. Our extensive simulation results reveal that GCA achieves improved performance over existing channel assignment protocols designed to consider performance anomaly.



## 1. Introduction

Wireless networks based on the IEEE 802.11 technology are increasingly deployed to accommodate a large volume of Internet traffic in commodity networks. IEEE 802.11 wireless networks provide connectivity to homes and offices in rural or metropolitan environments through self-configuring wireless links in an ad hoc fashion. The network capacity of IEEE 802.11 networks is severely degraded as the number of flows and node density increase. One effective solution to leverage the network capacity is utilizing multiple channels. By allowing multiple transmissions at the same time, the network capacity of IEEE 802.11 wireless networks can be improved.

In multi-channel multi-radio IEEE 802.11 networks, nodes can use multiple IEEE 802.11 interfaces [1]. IEEE 802.11 specifications provide a limited number of non-overlapping channels. For instance, IEEE 802.11a supports 12 non-overlapping channels and IEEE 802.11b supports three non-interfering channels. Moreover, nodes equipped with IEEE 802.11 interfaces should obey the *interface constraint*. That is, the number of allocated channels on a node cannot be larger than the number of equipped interfaces per node. This fact severely restricts the number of concurrent transmissions. Extensive multi-channel protocols have been suggested to use multiple available channels and interfaces efficiently [2–16].

In addition to multi-channel capability, off-the-shelf IEEE 802.11 devices also support multiple data rates depending on the wireless channel condition. For example, IEEE 802.11a provides 6, 9, 12, 18, 24, 36, 48, and 54 Mbps, and IEEE 802.11b offers 1, 2, 5.5, and 11 Mbps, which are used for data frame transmissions. Data transmissions

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with different data rates can be made on a common channel in wireless networks. However, it is well known that *performance anomaly* can occur when low-rate links and high-rate links share a same channel [17]. That is, low-rate links severely affect the performance of high-rate links on the same channel. There have been many research efforts to address this problem in single-channel multi-rate wireless networks [18–24].

We focus on mitigating the performance anomaly problem by utilizing multiple channels to separate link data rates in IEEE 802.11-based multi-radio multi-rate networks. This scheme has several important features as follows: (i) High-rate links are separated from low-rate links through available channels so that performance anomaly is addressed. (ii) Both high-rate links and low-rate links can be activated in parallel by exploiting non-overlapping channels. This feature enables concurrent transmissions for improved network performance. (iii) No extensions to legacy IEEE 802.11 devices are required. This feature makes our work suitable for commodity IEEE 802.11-based networks.

In this paper, we introduce the concept of rate conflict graph (RCG), which is an extension of the conflict graph, to model the performance anomaly behavior in IEEE 802.11-based multi-rate networks. Then, we propose a group-based channel assignment (GCA) protocol to consider the performance anomaly problem in IEEE 802.11-based multi-radio multi-rate single-hop ad hoc networks. In GCA, each node has multiple interfaces and performs channel assignments of available links by using RCG and *component group*. Depending on the number of equipped interfaces and established links in the network, links are subdivided into a single or multiple component group(s) by obeying the interface constraint. Then, GCA performs the group rate separating (GRS) algorithm to assign channels of links in each component group. The GRS algorithm distributes different rate links over multiple channels by considering network throughput and fairness of link throughputs. Our extensive simulation results show that GCA outperforms existing multi-channel protocols which are developed to mitigate the performance anomaly problem in IEEE 802.11-based multi-radio multi-rate single-hop networks.

Our contributions in this paper can be summarized as follows. First, the proposed protocol models the performance anomaly problem by using an extended conflict graph, called RCG. Second, our protocol uses the concept of component and component groups to utilize all the available channels with a small number of interfaces per node. This increases the number of concurrent transmissions and improves the network performance significantly. Third, we propose an efficient heuristic channel assignment algorithm to separate different data rate links in each component group by using RCG. Last, extensive simulations verify that the proposed protocol shows improved performance compared with existing channel assignment protocols designed for performance anomaly mitigation.

The paper is organized as follows. In Section 2, we survey related work. Then, we give problem formulations in Section 3, and propose the GCA protocol in Section 4. We evaluate the performance of GCA by comparing with existing protocols in Section 5, and finally conclude this paper in Section 6.

## 2. Related work

Many researchers have proposed multi-channel protocols to improve the capacity of IEEE 802.11-based wireless networks. To utilize multiple channels with one or a small number of interfaces, several dynamic channel assignment protocols have been developed [2,3]. For example, multi-channel routing (MCR) classifies available interfaces into fixed interfaces and switchable interfaces [2]. Allocated channels for fixed interfaces are almost static, while switchable interfaces can switch their channels dynamically. In multi-channel MAC (MMAC), each node has a single interface and nodes are synchronized by using beacon messages [3]. In control phases, a pair of nodes reserves one channel for data transmissions, while actual transmissions occur on the channel in data phases.

Also, extensive channel assignment protocols [4–16] have been proposed for wireless mesh networks (WMNs) [25]. For example, *Hyacinth* constructs one or more tree architecture from gateway nodes by using multiple channels and interfaces [4]. In [5], the joint channel assignment and routing problem is formulated to address the interference constraints and the number of channels and interfaces in WMNs. Then, the formulation is used for optimizing the network throughput. In [6], the capacity of WMNs is characterized to achieve optimal performance by proposing routing, link channel assignment and scheduling algorithms. In [7], an optimal algorithm is proposed for interference-aware topology control and QoS routing in WMNs.

To overcome the performance anomaly problem, many efforts have been made [18–24,26,27]. These efforts typically modify the IEEE 802.11 standards. For instance, a scheme proposed in [18] handles the problem at AP by controlling the number of frames transmitted through low-rate links. In [19], authors proposed remedies to control access parameters of IEEE 802.11 such as the initial back-off window, the frame size, and the maximum back-off stage. In [20], the minimum contention window in IEEE 802.11 is adjusted in a distributed manner. In [21–23], a common scheme is proposed to exploit cooperation among nodes for frame relaying. Opportunistic auto rate (OAR) is developed to utilize time diversity [24]. OAR transmits data frames in a back-to-back way to exploit high quality links opportunistically. These protocols assumed single-channel networks. As an extension to OAR for multi-channel networks, multi-band OAR (MOAR) is designed [26,27]. In MOAR, single interface equipped nodes skip frequency channels in search of high quality channels to exploit frequency diversity, which is considerably different from our work that focuses on rate separation by using multiple channels.

Several protocols have been explored for rate separation that uses multiple channels to mitigate the performance anomaly problem in IEEE 802.11 multi-radio multi-rate networks. These protocols assumed multi-hop networks [28–31] or single-hop networks [32,33]. For