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Robust resource allocation for multi-hop wireless mesh networks with end-to-end traffic specifications

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ABSTRACT

In this paper, we consider the robust resource allocation problem targeting for providing end-to-end rate guarantee in multi-hop multi-radio multi-channel wireless mesh networks. We incorporate the concepts of interference margin and outage probability to characterize the network robustness under *homogeneous* and *heterogeneous* wireless channel conditions. The robust resource allocation problems are formulated as mixed-integer nonlinear programming (MINLP) problem by explicitly taking into account practical radio switching, co-channel contention and multi-path routing constraints. To reduce the complexity, we exploit the special property of the problems and decompose them into the feasibility-checking problem, and propose a binary search algorithm to find the optimal solution of the problems using an iterative procedure. Using traces collected from an indoor wireless testbed, we evaluate the proposed algorithms in terms of interference margin and outage probability. The simulation results show that our algorithms are superior to existing scheme under moderate channel variations and external interference.

1. Introduction

Wireless mesh network (WMN) is deemed as a promising technology for next-generation wireless broadband provisioning due to many advantageous properties, such as easy to deploy, self-organization, self-management, and self-healing [1,2]. One of the salient features of WMNs is its flexibility in supporting multi-radio and multi-channel (MR–MC), which has been exploited to achieve different objectives, such as improving the network capacity [3–8], minimizing the interference [9,10], and reducing the congestion delay [11]. These research work demonstrate that MR–MC wireless mesh network can reduce the co-channel contention and improve the network capacity significantly, which make it especially attractive for providing services to QoS-sensitive applications, such as wireless visual surveillance, video streaming, and VoIP.

The obstacle for providing guaranteed services in WMNs comes from two sources, one is the innate dynamics of wireless channel, the other is the non-manageable interference from external wireless devices, which may deteriorate the performance of WMNs significantly if the network resources are not carefully managed. In this paper, we consider the problem of providing rate guarantee for unicast sessions with end-to-end traffic demand in WMNs under moderate channel dynamics and external interference. This work is motivated by our previous work [12,13], wherein we study the problem of maximizing the *robustness* of wireless networks, which is characterized by the *interference margin* of wireless links. Unlike [12,13], which assumes that the link-level traffic demands are given, we consider a general case whereby each unicast session has an end-to-end traffic demand, and the traffic of each session can go through multiple paths. Therefore, multi-path routing and traffic splitting have to be jointly

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optimized with other network resource allocation mechanisms such as channel assignment and rate selection.

To account for the dynamics of wireless channel, we consider two channel models in this work, one is the *homogeneous* wireless channel, the other is the *heterogeneous* wireless channel. For the *homogeneous* wireless channel, we assume that the channel variations are homogeneous for different links, and the quality of each wireless link can be characterized with its mean value (which is in general determined by the path loss between two ends of the link). For this case, we formulate the resource allocation problem as a *Robust Interference Margin* (*RIM*) optimization problem, the objective is to maximize the interference margin of each individual link so as to improve the capability for tolerating moderate external interference and channel variations.

For the *heterogeneous* wireless channel, we assume that different links may have different channel variations. In this case, the performance of highly dynamic links is worse than other links since the interference margin of different links may not be optimized according to their variations. Motivated by the measurement results in [14], we model the wireless channel as a lognormal random variable whereby the link quality can be characterized by both the mean and the variance (which can be obtained from the measurement results). Based on this model, we can derive the outage probability for each individual link, which is the probability that the perceived signal-to-interference-plus-noise ratio (*SINR*) is below a certain threshold specified by the corresponding transmission rate. We introduce the notation of *outage probability based interference margin* (OPIM), which can distinguish links with different channel dynamics. Similar to the previous case, the *Robust Outage Probability based Interference Margin (ROPIM)* problem is formulated to optimize the OPIM of each individual link so that moderate external interference can be tolerated while ensuring the outage probability requirement of each link is satisfied.

For both scenarios, the resource allocation problems can be formulated as a joint optimization problem of radio-channel assignment, rate selection, multi-path routing and traffic splitting. The challenges for these robust resource allocation problems are twofold. First, a wireless link in a MR–MC network is ready for transmission only if both the transmitter and receiver are operating at the same channel, so extra mechanisms are needed for coordinating the transmission if the radios at two end nodes of a link are assigned to different channels. Second, the formulated optimization problems involve the channel and rate selection (combinatorial constraints), and multi-path traffic splitting (continuous constraints). These problems belong to the class of mixed-integer nonlinear programming (MINLP) problem, which is known to be NP-hard and no efficient solutions exist in general.

We overcome these barriers as follows. To resolve the coordination problem, we adopt a practical radio switching scheme proposed in [15]. Specifically, the radios at each node are classified into two categories, one is the *fixed* radio that is dedicated to a specific channel, the other is the *switchable* radio that can be tuned among different channels as necessary. A node can transmit packets to its neighbors by tuning the channel of its *switchable* radio to be same as the fixed radios of neighboring nodes, thus no coordination is needed between nodes. To reduce the complexity of the MINLP problems, we exploit the special property of these problems and decompose them into a feasibility-checking problem and a binary search problem. The former one is obtained by eliminating the nonlinear parts of the original problem and reducing the number of binary variables, thus the optimal solution can be obtained with less complexity, and the latter one adopts a binary search procedure that is guaranteed to converge to the optimal solution.

The rest of the paper is organized as follows. In Section 2, we discuss some existing research work relevant to our work. The network models assumed in this paper are introduced in Section 3. The *RIM* problem for homogenous wireless channel and the decomposition procedure is proposed in Section 4. In Section 5, we proceed to discuss the channel model for heterogenous wireless channel and propose the ROPIM problem. Simulation results are provided in Section 6 to demonstrate the performance of the proposed schemes using real-world trace data from an indoor wireless network testbed. Finally we conclude this paper in Section 7.

2. Related work

Many resource allocation schemes for MR–MC wireless networks have been proposed in literature. They can be roughly categorized as, traffic-agnostic [16,9] vs. traffic-aware [17,18,12], assuming binary [18,7,4,17] vs. physical interference and link capacity model [16], centralized [18,7,4,17] and distributed schemes [9,16]. In [6], Rad et al. consider the joint channel allocation, interface assignment and media access control problem, which is formulated and solved as a nonlinear mixed-integer network utility maximization problem. In [19], Lin et al. devise a distributed algorithm for jointly solving the channel assignment, scheduling and routing problem assuming the traffic demands are not known. The proposed scheme is throughput optimal in terms of stability when the traffic demands approach the capacity limit. However, it may suffer from high latency and slow convergence in presence of channel variability in large networks.

Most existing resource allocation schemes are based on some well-accepted channel models such as the free-space model or the two-ray ground model. Recent studies [20,21] show that these models are inaccurate for prediction of link-level interference, especially in the indoor environment where the radio signal degrades much faster than that in free space environment. Therefore, there has been some recent work that incorporate the measurement results into the interference modeling [14], link capacity prediction [22], and conflict graph construction [18,17,9,7].

Very little work addresses the issue of robustness in wireless networks. In [23], Kandukuri et al. derive the link outage probability and incorporate it into the power control problem for interference limited wireless networks. However, the analysis is only applicable for Rayleigh fading channel. In [24,25], the robust optimization techniques