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Resource planning and packet forwarding in multi-radio, multi-mode, multi-channel, multi-rate (M^4) wireless mesh networks ☆

Ting-Yu Lin [a,*], Wai-Hong Tam [b], Kang-Lun Fan [a], Yu-Chee Tseng [b]

[a] *Department of Communication Engineering, National Chiao-Tung University, 1001 University Road, Hsinchu 300, Taiwan*
[b] *Department of Computer Science, National Chiao-Tung University, 1001 University Road, Hsinchu 300, Taiwan*

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Abstract

Most earlier works in the area of wireless mesh network assume a single interface being equipped in each node. In this paper, we consider the next-generation wireless mesh networks in which each node may be equipped with multiple radio interfaces, each capable of running in one of several modes (IEEE 802.11b/g 2.4 GHz or 802.11a 5 GHz mode), one of several channels, and each capable of supporting multiple modulations. We call such a network an M^4 (multi-radio, multi-mode, multi-channel, multi-rate) wireless mesh network. For example, from off-the-shelf components, one can easily construct a mesh node with multiple IEEE 802.11a/b/g radio interfaces. Our goal is to address the resource planning and packet forwarding issues in such an environment. The proposed methodology is based on linear programming with network flow principles and radio channel access/interference models. Given a network topology, traffic requirements, and gateway capacities, we show how to allocate network interface cards and their channels to fully utilize channel bandwidths. The results can be utilized by a wireless Internet service provider to plan their networks under a hardware constraint so as to maximize their profits. To the best of our knowledge, this is the first work addressing resource planning in a wireless mesh network. Our numerical results show significant improvement in terms of aggregate network throughput with moderate network-layer fairness. The importance of network planning is further corroborated by the simulative comparisons with other multi-radio systems assuming a known and fixed number of interfaces at each mesh router.

Keywords: Resource planning; Routing; Channel assignment; Linear programming; Wireless ad hoc network; Wireless mesh network

1. Introduction

The wireless mesh network (WMN) is a promising solution to the last-mile wireless Internet access problem. It can effectively complement the limitation of WLAN coverage. Applications of WMN include enterprise wireless backbones and community networks [15]. In [5], two mesh hierarchies are defined: *infrastructure mesh* and *client mesh*, where the former has much less mobility than the latter. Ref. [14] points out that a WMN may suffer from the scalability problem as the network grows due to the contention and interference among hosts. To mitigate the scalability problem, one may explore advanced transmission technologies (such as smart or MIMO antennas [11,17,22]) or layer-2 or layer-3 solutions based on commodity radio modules [3,6,8,12,9,16,18,19,21]. Several works show how to increase WMN capacity by adaptively adjusting the data rates [4,7,13,20].

In this work, we adopt the latter approach based on commodity components. We explore the possibility of multi-interface, multi-channel model. For example, IEEE 802.11a/b/g has 12/3/3 non-overlapping channels available. One can easily make a multi-interface mesh node by off-the-shelf components.[1] Several works have addressed

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* Corresponding author. Tel.: +886 921 591603.
E-mail address: tylin@csie.nctu.edu.tw (T.-Y. Lin).

[1] With the advance of communication hardware technology, and cost-reduced networking modules, nowadays computing devices are often capable of operating/communicating on/through different radio frequencies (e.g., WiFi/Bluetooth/WCDMA possibly readily available at a single laptop, which may be installed with another WiFi card via the PCMCIA interface). Hence, equipping multiple wireless interfaces at a single host is getting affordable and its popularity can be expected in next-generation wireless-enabled computers.

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the related issues. In [10,24,25], the authors propose to use a dedicated interface running on a control channel to negotiate the data channels to be used by other interfaces. Refs. [3,6,8,12,16,18,19] propose to treat interfaces equally and some channel assignment techniques are used to exploit spatial reuse.

The above works all assume that the number of interfaces in each mesh node is given. In this paper, we address the resource planning problem in a multi-radio multi-mode multi-channel multi-rate (M^4) wireless mesh network. Our approach is based on linear programming. Based on the well-known IEEE 802.11 channel contention model, we compute the near-optimal number of radio modules that should be equipped in each node and the channel that should be bound with each interface. We present two resource management and channel assignment algorithms: Decremental Interface Management (DIM) and Incremental Interface Management (IIM).

Our ultimate goal is to maximize the traffic volume in/out of Internet gateways of the mesh network, under the restrictions of network topology (connectivity status), available resources, and user's traffic needs. We summarize our contributions as follows:

- Instead of considering only a single factor, our approach addresses all practical characteristics of wireless communications, including the available non-overlapping radio channels and the interference factors among neighboring mesh nodes.
- Resources are allocated to mesh nodes based on user's traffic requirements, available hardware/radio modules, and gateway capacities. We allow nodes to have different numbers of radio interfaces. Not only addressing the related multi-channel issues, we also provide a guideline to wisely distribute the deployment costs considering an optimized network system. To the best of our knowledge, this is the first work addressing resource planning in wireless mesh networks.
- In order to enable simultaneous traffic incoming/outgoing through different radio modules of the same mesh host, we propose to perform multi-path packet forwarding (data flow splitting) to further exploit the benefits of having multiple transceivers. This idea will be elaborated in more detail in Section 3.4.

The remaining paper is organized as below. Section 2 reviews past related work in M^4 wireless mesh networks. In Section 3, we introduce the M^4 network architecture, our linear programming model for network optimization, two resource management and channel assignment algorithms, and our packet forwarding strategy. Section 4 presents the numerical and simulation comparison results. Finally Section 5 draws our conclusions and future plans.

2. Related work

The design of multi-channel WMN has been investigated in several works [3,8,9,12,16,18,19,21]. These works treat all channels equally based on the IEEE 802.11 MAC mechanisms and have a goal of minimizing the contention among wireless links. A *single-transceiver* model is assumed in [9,21], while a *multi-transceiver* model is adopted in [3,6,8,12,16,18,19]. For a single-transceiver system, the radio interface in each node needs to switch among channels. This will results in the *multi-channel hidden-terminal problem* [21]. So the authors in [21] proposed to embed a negotiation phase in the ATIM (Ad Hoc Traffic Indication Map) window that is periodically sent under the Power Save Mode (PSM). Every node has to go to a predefined control channel when entering the ATIM window. The negotiation phase is to determine data channel to be used after the ATIM window finishes. The Slotted Seeded Channel Hopping (SSCH) mechanism [9] divides the time axis into virtual channels. Each virtual channel's hopping sequence is determined by a (channel, seed) pair. Whenever a sender wishes to communicate with a neighbor, it changes its hopping schedule to the receiver's in the corresponding virtual channel. SSCH requires a looser time synchronization than [21], but its channel switching overhead is high.

Refs. [3,8] pointed out the advantage of equipping multiple radio interfaces on a single mesh node. Such system can alleviate both *inter-route* and *inter-hop* contentions. As shown in Fig. 1, two data paths A-B-D and A-C-E both operating on channel 1 cannot be active at the same time, due to inter-route contention. The two data flows can be made active simultaneously by adding one more interface binding to channel 2 on node A and switching nodes C, E to operate on channel 2, removing the inter-route contention (Fig. 1(a)). However, since wireless links A-B and B-D use the same channel 1 along the A-B-D route, the contention between consecutive hops remains. By adding another radio modules on nodes B, C and switching nodes D, E to channels 3, 4, respectively, the inter-hop contention problem can be further eliminated, so that links A-B, B-D, A-C, and C-E now become interference-disjoint and can be made active simultaneously (Fig. 1(b)). Note that designing

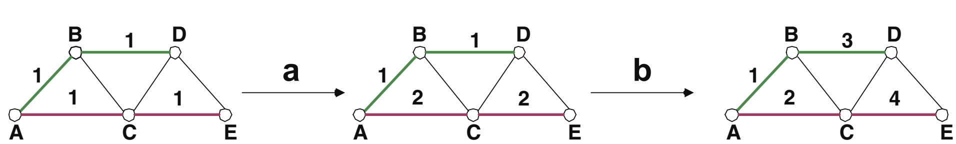

Fig. 1. Illustration of the multi-radio benefits (the number associated with each edge indicates the channel number used): (a) enabling simultaneous transmissions between routes (*inter-route* contention removed); (b) further enabling simultaneous transmissions between consecutive hops along a route (*inter-hop* contention eliminated).