

Efficient Interference-aware Channel Allocation in Multi-radio Wireless Mesh Networks

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Abstract—In wireless mesh networks, mesh nodes equipped with multiple radios tuned to multiple non-overlapping channels bring high network performance. As wireless mesh networks have been deployed in the urban area, dynamic channel allocation is more challengeable because co-located wireless networks are likely to be tuned to the same channels and may interfere with communication. This paper proposes an interference-aware channel allocation algorithm considering an external interference for multi-channel multi-radio wireless mesh networks. Each mesh node uses a novel technique to estimate the usage status of all the channels within its interference range and assigns channels dynamically to radios to minimize interference within the mesh network and between the mesh network and co-located wireless networks. Simulation results demonstrate that our proposed algorithm can improve the network throughput substantially compared to a channel allocation regardless of external interference.

I. INTRODUCTION

Today, the demand for expanded WLAN coverage is greater than ever, driven by the increasing number of computing and communications devices that are equipped with an integrated IEEE 802.11 WLAN interface - including smart-phones, notebook PCs and multimedia components. Due to their easiness-to-deploy and self-healing features, wireless mesh networks (WMNs) are emerging as a new promising technology. WMNs greatly expand the coverage area of today's WLAN technology and help overcome many of its deployment challenges.

As WMNs collect and relay the traffic generated by many clients, there have been several research efforts to improve the network capacity and one of the strategies is by coordinated use of multiple channels and multiple radios. IEEE 802.11 offers multiple non-overlapping channels. For example, IEEE 802.11b offers 3 non-overlapping channels, while IEEE 802.11a offers 12 non-overlapping channels. By assigning the multiple radios to these channels, mesh nodes are capable to transmit and receive data simultaneously with minimal interference.

Thus, the channel assignment to a mesh node becomes an important research issue. In previous studies [1], [2], [3], many researchers mainly focus on the issue of efficient channel assignment between mesh nodes within interference range. The proposed solutions typically consider the number of mesh nodes sharing each channel, the traffic load, and capacity requirements. However, they do not consider the effect of

interference from co-located wireless networks, such as uncoordinated IEEE 802.11 hotspots. These co-located wireless networks are likely to be tuned to the same channels of mesh nodes and the external interference can adversely affect network performance. [4], [5] suggest centralized assignment algorithms considering not only internal mesh channel usage but also external interference. However, these protocols have their problems. For example, it is difficult for a centralized assignment algorithm to efficiently adapt to rapidly and unpredictably varying wireless environments and it induces additional delay for channel assignment. Moreover, the external interference can be overestimated more than the real amount of it because some external nodes are monitored by adjacent mesh nodes at the same time. As a result, the central channel allocation server (CAS) assigns the invalid channels to mesh nodes.

In this paper, we propose novel distributed interference-aware channel allocation algorithms aimed at improving the capacity of wireless mesh networks. These algorithms intelligently select channels for the mesh radios in order to minimize interference within the mesh network and between the mesh network and co-located wireless networks. We also suggest a novel method for the interference estimation considering the problem of external interference overestimation. All available channels are periodically monitored by each mesh node and measured information of internal channel usage and external interference is shared with mesh nodes within interference range.

The rest of the paper is organized as follows. We describe related work in Section II. The channel assignment problem and assumptions are defined in Section III. Sections IV and V describe the details of the proposed approaches. We evaluate our proposal in Section VI and conclude in Section VII.

II. RELATED WORKS

There have been a considerable number of researches on efficient channel assignment for multi-radio multi-hop wireless mesh networks. In early researches, many researchers mostly focus on the issue of efficient channel assignment between mesh nodes within interference range. The proposed solutions typically consider the internal channel usage which is depend

on the number of mesh nodes sharing each channel and the traffic load.

In [1], mesh nodes announce the current occupied channel to neighbor nodes by periods. If the number of other nodes using the same channel as itself is large, then a node with some probability changes its channel to a less used channel. In [2], each mesh node periodically exchanges its individual channel usage information with all its neighbors within interference range. The aggregate traffic load of a particular channel is estimated by summing up the loads contributed by all the interfering neighbors. The total usage of a channel is a weighted combination of the aggregated traffic load and the number of nodes sharing the same channel.

Recently, [4], [5] suggest a centralized assignment algorithms considering not only internal mesh channel usage but also external interference. Since mesh nodes are not able to share the channel usage information directly with external nodes, we should estimate the amount of external interference. In [4], each mesh node periodically monitors all available channels and it uses the captured packets to measure per second external interference. The mesh node then derives channel rankings. This channel ranking is according to the increasing external interference. The channel ranking result of each mesh node is sent to the central channel allocation server (CAS). After the CAS obtains channel rankings from all mesh nodes, it chooses the set of channels minimizing the network interference and notifies mesh nodes to reassign their radios to the chosen channels. However, these protocols have their problems. For example, it is difficult for a centralized assignment algorithm to efficiently adapt to rapidly and unpredictably varying wireless environments and it causes additional notification delay for the channel assignment. And the channel's rank information is only able to determine the relative good or bad state of channels. Then, the CAS loses the information about the existence of external nodes and the gap of interference between channels. In [5], the proposed algorithm overcomes this ranking problem by sending per second external interference to CAS instead of ranking information. However, it also has a problem that the external interference can be overestimated more than the real amount of it because some external nodes are monitored by adjacent mesh nodes at the same time. As a result, the CAS assigns the invalid channels to mesh nodes.

This paper addresses novel interference-aware channel allocation algorithms performed in a distributed manner. These algorithms select channels for the mesh radios in order to minimize interference within the mesh network and between the mesh network and co-located wireless networks. Moreover, a novel method for the interference estimation solves the problem of external interference overestimation. Section IV and V describe the details.

III. PROBLEM STATEMENT AND ASSUMPTIONS

A. Problem Formulation

In this paper, our primary goal is to select the least used channel within the collision domains of sender and receiver to

resolve contention and to minimize collision probability in a distributed manner.

Within the collision domain, internal mesh nodes share channels with external nodes, such as WLAN nodes based on IEEE 802.11. In this paper, we do not consider external interference from non-IEEE 802.11 access networks. Thus, all nodes utilize the Distributed Coordination Function (DCF) and share the channel within the same vicinity. Therefore, the lower the traffic load on the channel by other nodes, the more residual channel capacity is available to the node of interest.

The channel utilization on each channel can be represented as the traffic load within the collision domain and it is the metric for selecting the least used channel. Channel utilization is calculated as the sum of internal channel usage used by mesh nodes and external interference used by external nodes. Although the amount of internal channel usage generated by other mesh nodes can be known precisely through the announcement between mesh nodes, it is hard to know the amount of external interference because there is no cooperative communication with external nodes. Therefore, we can only estimate the amount of external interference through the measurement of external traffic load and the precise prediction is important to select the least used channel.

In addition, the channel assignment priority should be given to heavily loaded mesh nodes. Mesh nodes that need to support higher traffic load should select a channel having more residual bandwidth than others. However, as nodes need more bandwidth, the number of channels satisfying that requirement is small. In the worst case, these nodes find no available channels if the channels are preempted by lightly loaded nodes. Therefore, heavily loaded nodes should have higher priority than other nodes during the channel assignment to use all available channels effectively.

B. Network Model

As shown in Fig. 1, the wireless mesh network (WMN) consists of N mesh nodes. At least one mesh node is designated as a gateway connected with the wired network via high capacity cable and is called mesh portal (MPP); the rest of WMN are comprised of mesh points (MP) that relay clients' traffic to and from the wired network and mesh access points (MAP) that are mesh points supporting access point service. In order to simplify the explanation of the channel assignment solution, we assume the presence of only one MPP. Mesh nodes are stationary and the topology is changed only when there is an additional installation or failure of nodes [6]. Although the proposed algorithms support multiple radios, we assume that each mesh node is equipped with two backhaul radios. In theory, a mesh node can be equipped with many backhaul radios. However, network performance is not improved as much as increasing the number of radios [7]. Moreover, the inter-radio interference problem gets worse with many equipped radios and it causes performance degradation [8]. MAPs can be equipped with an additional radio to support mobile client access. To separate the user traffic from WMN

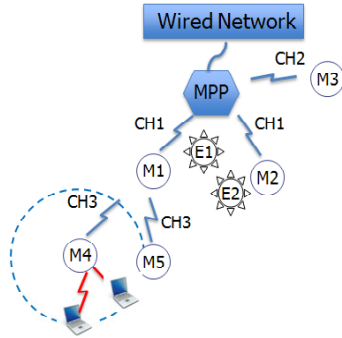


Fig. 1. Wireless mesh network architecture

backhaul, the 2.4GHz band is usually used for mobile clients and 5GHz band is used to support backhaul traffic.

Most traffic through the mesh network is mainly directed toward the MPP (i.e. the traffic is directed to/from the Internet). As a result, the route path is likely to be formed as a tree structure where the MPP is a root of the tree and each node has a parent node and children nodes. Among dual radios of each mesh node, one radio is used to communicate with its parent node, termed UP-radio, and the other radio is used to communicate with its children nodes, termed DOWN-radio. As an exception, the MPP has two DOWN-radios. Each node is responsible for assigning a least used channel to its DOWN-radio. Each node's UP-radio is associated with the DOWN-radio of the parent node and is assigned the same channel corresponding the parent's DOWN-radio.

In the network model, we do not use common channel and common radio to prevent additional hardware overhead and waste of resources. Instead, we exchange all control traffic such as packets for route discovery and state announcement by forming a virtual control network [2]. Since there is always a tree path between a mesh node and its physical neighbors, control packets including not only unicast but also broadcast can be delivered through multiple hops on the mesh network. We do not present the detail of formulation of virtual control network due to space limitations.

C. Interference Model and Assumptions

All mesh nodes and IEEE 802.11 based external nodes utilize the Distributed Coordination Function (DCF) to handle multiple access. To transmit a packet, a sender node firstly senses the channel and differs the transmission. After sensing an idle, the mesh node sends the packet to receiver node. Although the sender sends a packet during idle period, the receiver cannot receive the packet correctly because there is still collision probability among multiple nodes close enough to the receiver. Therefore, a mesh node should know the utilization of all channels within not only its interference area but also the union of its children's interference areas to assign a channel to its DOWN-radio. In the next section we present details of the estimation of channel utilization within the interference area.

IV. INTERFERENCE ESTIMATION

Each mesh node is responsible for assigning a channel to its DOWN-radio to communicate with its children. Among available channels, the least used channel is selected for DOWN-radio of the mesh node and the metric is represented as the channel utilization. Channel utilization is calculated as the sum of internal channel usage used by mesh nodes and external interference used by external nodes. Although the internal channel usage generated by other mesh nodes can be known easily through the announcement between mesh nodes, we can only estimate the amount of external interference through the measurement of external traffic load. Therefore, the precise prediction of external interference is important to select the least used channel.

A. External Interference Estimation

1) *Measurement of external interference:* To measure the external interference, each mesh node captures packets from the medium. Commercial network devices usually support variable receive modes to capture packets, for example promiscuous mode and RFMon mode. The promiscuous mode only captures data packets and does not capture IEEE management packets. On the other hand, the RFMon mode allows capturing both regular data packets and IEEE management packets in the media. Thus, it is more suitable for the precise prediction of external interference. Using the RFMon mode, mesh nodes know the information of captured packet, such as sender ID and size of packet and they can estimate external traffic load.

To estimate external interference of all available channels, each mesh node periodically switches its DOWN-radio and measure the external interference of all channels. However, while the DOWN-radio is used for the measurement of external interference, the links with children are disconnected. Adding a common radio is a simple way to solve this problem as [4] and [5], we do not use this approach. Instead, each mesh node sends a temporal channel change message containing its UP-radio's channel information to children before starting the measurement. Then, all children receiving this message change its UP-radio's channel to the parent's UP-radio's channel during the measurement period. As a result, the mesh node starting the channel measurement maintains links with children using its UP-radio.

2) *Announcement of external interference:* Each mesh node captures packets from the medium by using RFMon mode, but it is possible only within the transmission range. Since, received packets from the outside of the transmission range are not able to decode, it is not possible to decide packets between the internal traffic and external traffic. However, a mesh node should know the external interference all channels within not only its interference area but also the union of its children's interference areas. We assume that k is the ratio of the interference range and the communication range. Then, each mesh node needs the information of external interference measured by all its $(k + 1)$ -hop neighbors. Each node therefore periodically exchanges its measured external interference information as a CHAN_UTIL packet with all its

$(k + 1)$ -hop neighbors. This packet is exchanged through the virtual control network without common channel and common radio.

3) *Elimination of overlapped external interference:* Physically adjacent mesh nodes can capture same packets from same external nodes simultaneously during the measurement of external interference. As shown in Fig. 1, packets from external nodes (E1 and E2) are captured by mesh nodes (MPP, M1 and M2) simultaneously. After that, each mesh node exchanges its measured external interference information as a CHAN_UTIL packet with all its $(k + 1)$ -hop neighbors. As a result, each mesh node receives overlapped information and estimated external interference becomes 3 times bigger than real interference. Consequently, the channel utilization is calculated incorrectly. Therefore, mesh nodes maintain the external interference by the external sender ID. If the external interference is maintained by the external sender ID, it is possible to check the overlapped part and eliminate that part. To do so, the CHAN_UTIL packet contains the measured traffic load by external sender ID separately.

B. Internal Channel Usage Announcement

Each mesh node is equipped with two backhaul radios and two difference channels are assigned to communicate with its parent and children. The mesh node measures individual channel usages of two operating channels continuously. When the measured external interference information is exchanged with its $(k + 1)$ -hop neighbors, the information of internal channel usages are also included in the CHAN_UTIL packet. Since each mesh node exchanges the amount of internal channel usage generated by its radios, other mesh nodes can know the exact amount of internal channel usages within the interference area.

V. DISTRIBUTED INTERFERENCE-AWARE CHANNEL ALLOCATION ALGORITHMS

We propose novel distributed interference-aware channel allocation algorithms considering the channel utilization. Each mesh node periodically confirms that DOWN-radio's current channel is overloaded. If the mesh node finds that the channel is overloaded, it selects the least used channel within the collision area and assigns it to its DOWN-radio. Moreover, heavily loaded nodes should have higher priority than other nodes to use all available channels effectively. According to the criteria of least used channel, conservative algorithm and aggressive algorithm are proposed.

A. Conservative Algorithm

The channel utilization on each channel can be represented as the traffic load within the collision domain and it is calculated as the sum of internal channel usage used by mesh nodes and external interference used by external nodes. We define node x 's channel utilization on channel c as

$$U_x(c) = L_x^I(c) + L_x^E(c), \forall c \in C \quad (1)$$

$$L_x^I(c) = \sum_{i \in N_x^I} l_i^I(c) \quad (2)$$

$$L_x^E(c) = \sum_{j \in N_x^E} l_j^E(c) \quad (3)$$

where $L_x^I(c)$ is the aggregated internal channel usage on channel c , $L_x^E(c)$ is the aggregated external interference on channel c , N_x^I is a set of mesh nodes within the collision domain of node x , N_x^E is a set of external nodes within the collision domain of node x , $l_i^I(c)$ is measured internal traffic of mesh node i on channel c , and $l_j^E(c)$ is measured external traffic of external node j on channel c .

As mesh nodes higher up in the tree need more relay bandwidth, they are given a higher priority in channel assignment. To do so, the mesh node restricts the least used channel that are not used by any of its interfering mesh neighbors having a higher priority. Therefore, the mesh node selects the least used channel for the DOWN-radio as

$$\overline{C}_x = \arg \min_c (U_x(c)), C_x^* \subset C \quad (4)$$

where, C is a set of all available channels, and C^* is a set of channels that are not used by any of its interfering mesh neighbors with a higher priority.

After the least used channel is selected, the mesh node confirms that the new channel is better than the current channel for improving performance. As shown in Fig. 2, if the MPP switches the channel from current channel i to new channel j , the performance is getting worse. Thus, we add a final condition of channel switching decision as

$$U_x(c_{cur}) \geq U_x(c_{new}) + l_x^I(c_{cur}) \quad (5)$$

B. Aggressive Algorithm

According to the conservative algorithm, although heavily loaded mesh nodes find the least used channel, they cannot switch the new channel if the channel switching does not improve network performance. In the aggressive algorithm, however, we can expect that a mesh node given a lower priority will change its channel to the other channels at the next channel assignment period. As shown in Fig. 3, after channel switching of the MPP from i to j , all internal mesh nodes change their channels at the next channel switching period because the MPP has the highest priority in the mesh network. As a result, the performance of MPP is improved. For the aggressive algorithm, some equations, Equation (1),(2),(4) and (5), are changed as

$$U_x^+(c) = L_x^{I+}(c) + L_x^E(c), \forall c \in C \quad (6)$$

$$L_x^{I+}(c) = \sum_{i \in N_x^I} l_i^{I+}(c), \begin{cases} l_i^{I+}(c) = l_i^I(c), & \text{if } c \in C_x^* \\ l_i^{I+}(c) = 0, & \text{else} \end{cases} \quad (7)$$

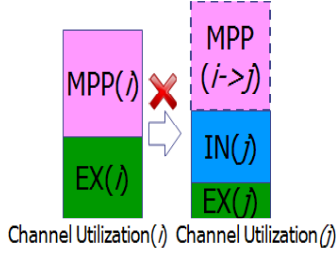


Fig. 2. Example of conservative algorithm

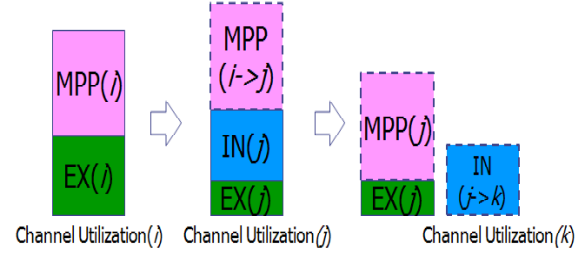


Fig. 3. Example of aggressive algorithm

$$\overline{C}_x = \arg \min_c (U_x^+(c)), C_x^* \subset C \quad (8)$$

$$U_x^+(c_{cur}) \geq U_x^+(c_{new}) + l_x^{I+}(c_{cur}) \quad (9)$$

VI. PERFORMANCE EVALUATION

The objective of the simulation-based evaluation is to verify the performance improvement by the proposed the interference estimation method and distributed interference-aware channel allocation algorithms in various environments.

A. Simulation Environment

For the performance evaluation, ns-2 simulator is used. We modify the simulator to support that each mesh node uses the multi-channel, multi-radio and captures packets from IEEE 802.11-based external nodes. All general parameters follow the standard of IEEE 802.11a and we consider the channel switching delay as 1ms.

25 mesh nodes are deployed in 5x5 grid topology without mobility. Each mesh node is away from its neighbors as much as the maximum transmission range and one MPP is located at the center of the topology. Considering the network size, 6 orthogonal channels are available and each mesh node has 2 backhaul radios. The link capacity is fixed as 54 Mbps and 12 CBR flows with 4Mbps are generated from the MPP to the randomly selected 12 mesh nodes.

In grid topology, the area surrounded by 4 mesh nodes is called a cell and there are 16 cells. A pair of external AP and external station is located in each cell. The positions of external nodes and used their channels are decided randomly.

The measurement period of external interference (T_M), the duration of capturing external packets on each channel (T_C), and the channel assignment period (T_A) depend on the variance of traffic flows in the real environment. In this simulation, we set the parameters as $T_M=40s$, $T_C=1s$, and $T_A=40s$ to understand the behavior of our algorithms as shown in Fig. 6. The simulation is sustained during 200s. And the ratio of the interference range and the communication range, k , is typically 2 [9].

B. Simulation Results

Fig. 4 illustrates the overestimation problem caused by overlapped information of external interference. If the external interference is maintained by channel based, it is not possible to check the overlapped part and eliminate that part. As the offered external traffic load increases, the amount of

overlapped part also increases. Consequently, the real external interference is overestimated and the channel utilization is calculated incorrectly. If mesh nodes maintain the external interference by the external sender ID based, they can estimate external interference precisely and select the correct least used channels.

Fig. 5 shows the performance comparison between conservative algorithm and aggressive algorithm. With conservative algorithm, although some heavily loaded mesh nodes find a least used channel, they cannot switch the new channel if the channel switching does not improve network performance. However, aggressive algorithm assigns the least used channel even though there is no improvement at the 120s. This algorithm expected that the network performance will be improved because mesh nodes given a lower priority changes its channel to the other channels at the 123s.

As shown in Fig. 6, we compared our aggressive algorithm against three other previous works in the grid topology. Each external flow is generated with 6Mbps. In the Genie-aid algorithm, we modify that all external nodes can send its traffic load information to mesh nodes within the collision domain. So, all mesh nodes can know the precise external interference. Therefore, it shows the optimal performance. Hyacinth algorithm does not consider the external interference to select the least used channel. As a result, there is no channel switching after the external interference occurs and the aggregated throughput is reduced to 8Mbps. In the Rama-Ranking algorithm, the channel's rank information is only able to determine relative good or bad channels. Since the CAS (central channel allocation server) loses not only the information about the existence of external nodes, but also the interference gap between channels, the incorrect least used channel is selected. On the other hand, aggressive algorithm recovers the throughput up to the result of the Genie-aid algorithm.

Fig. 7 presents the performance comparison between 4 channel assignment algorithms in 3 random topologies. The MPP and external nodes are located as same as the grid topology, but the 24 MAPs are located randomly in the simulation area with connectivity. As the MAPs are randomly located, there is estimation error of channel utilization. This is because there is no mesh node capturing the external packets within the transmission range of some external nodes. As similar as the result in grid topology, aggressive algorithm also selects the correct least used channel and shows better

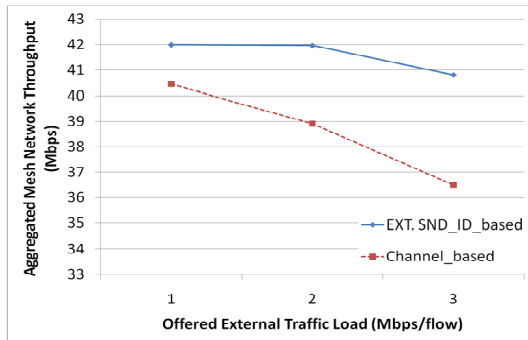


Fig. 4. External interference overestimation problem

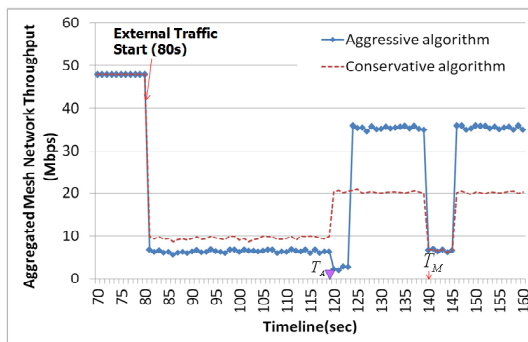


Fig. 5. Performance comparison between conservative algorithm and aggressive algorithm

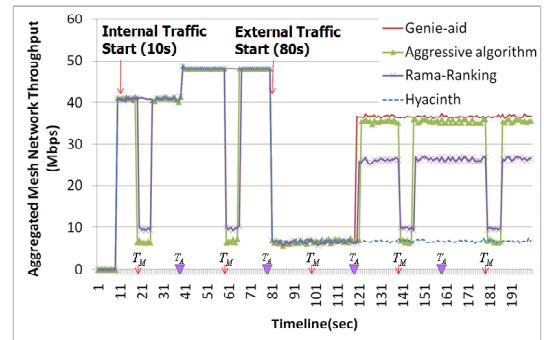


Fig. 6. Performance comparison between 4 algorithms in the grid topology

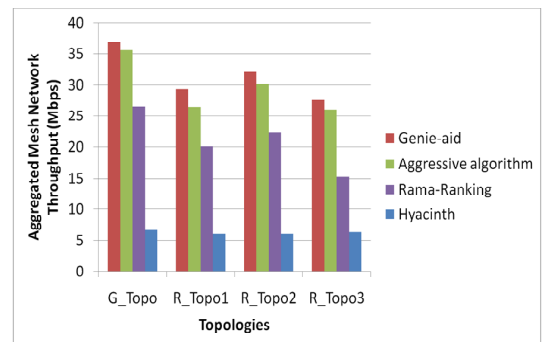


Fig. 7. Performance comparison between 4 algorithms in the random topology

performance than other proposed algorithms.

VII. CONCLUSIONS

As wireless mesh networks have been deployed, dynamic channel allocation considering co-located wireless networks is more challengeable because these networks are likely to be tuned to the same channels of WMNs. This paper proposes an interference-aware channel allocation algorithm considering an external interference for multi-channel multi-radio wireless mesh networks. Each mesh node uses a novel technique to estimate the channel usage status of all the channels within its interference range and assigns channels dynamically to radios to minimize interference within the mesh network and between the mesh network and co-located wireless networks. Simulation results demonstrate that our proposed algorithm can improve the network throughput substantially compared to other algorithms by removing the interference overestimation problem and assigning channels aggressively with priority.

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