

Weighted Conflict-Aware Channel Assignment in 802.11-based Mesh Networks

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Abstract—The hidden terminal problem, exposed terminal problem and co-channel interference problem are three main factors that limit the performance of wireless mesh networks. The network throughput can be increased by using multi-radio multi-channel technology through using different channels to avoid the collisions. In this paper, we provide a channel assignment scheme considering interference, hidden/exposed terminal problem all together. For this scheme, we first propose a weighted conflict model in multi-channel multi-radio wireless mesh networks and define a *Max list-Cut* problem on the weighted conflict graph. We present an approximation algorithm for the *Max list-Cut* problem to solve the channel assignment problem. Our simulation results show that the proposed channel assignment scheme achieves high network performance in various topologies.

keywords—Channel Assignment, Interference Problem, Hidden/Exposed Terminal Problem, Conflict Graph, Max list-Cut

I. INTRODUCTION

Wireless mesh networks (WMNs) are multi-hop networks which consist of static wireless devices that connect to each other and act as routers. Since WMNs are capable of self-configuring and ad-hoc networking, they can provide wide coverage with low maintenance costs. In a WMN based on the IEEE 802.11 standard, the wireless routers with a single half-duplex radio typically use a single channel [1]. Thus, unlike wired networks, signal interference occurs among nearby communications which results in the significant degradation of the network performance. To avoid the collision between nearby communications, the CSMA/CA protocol is adopted in the IEEE 802.11 LANs. Although the CSMA/CA protocol avoids simultaneous transmissions, transmission delay caused by the CSMA/CA protocol is inevitable with a single channel. Besides, two classic problems still remain from using the CSMA/CA protocol: hidden terminal and exposed terminal problems. If multiple orthogonal channels are available, network capacity can be increased by utilizing them. Moreover, we can prevent the hidden and exposed terminal problems by using different channels at the hidden or exposed terminals. Ideally, it is possible to avoid the hidden terminal problem, the exposed terminal problem and even interference problem without any network delay by assigning all distinct orthogonal channels to each communication link. Since the size and cost of the radio module are getting smaller and cheaper in recent years, it is affordable to equip wireless routers with multiple

radio modules to improve the network performance. Unfortunately, the number of available orthogonal channels is limited in IEEE 802.11 standards. With the IEEE 802.11b/g in the 2.4GHz band, three orthogonal channels are available and with the IEEE 802.11a in the 5GHz band, 12 orthogonal channels are allowed. With the finite number of orthogonal channels and radio modules, available orthogonal channels should be properly assigned to each communication link to maximize the capacity of networks without loss of connectivity. Thus, channel allocation problems have been widely studied [2], [3]. Based on the communication graph, interference appears between edges sharing a common vertex, so a channel assignment problem can be reduced to an edge coloring problem [4]. Instead of using a communication graph, Katzela and Naghshineh [5] extended the conflict graph to the multi-radio conflict graph to model interference between wireless routers. However, these researches mostly focused only on minimizing interference between allocated channels. Recently, Hammash et al. [6] shows that the hidden terminal problem is more related to performance degradation than interference. Thus, Hao et al. [1] proposed a channel allocation method considering both interference and hidden terminal problem. They regarded a 2-hop edge as a hidden terminal condition, but this is partially correct when the transmission, sensing and interference ranges are all different as we will explain details in Section II.

In this paper, we propose the channel assignment scheme considering the interference, hidden terminal, and exposed terminal problems to improve the network performance in multi-radio, multi-channel WMNs. To the best of our knowledge, it is the first approach considering three problems all together. We propose a *weighted conflict model* which represents the possible conflicts among communication links. Based on the weighted conflict model, we newly define the problem *Max list-Cut* to solve the channel assignment problem. We present an approximation algorithm for the channel assignment problem with the performance guarantee. The proposed algorithm preserves the network topology so it does not influence the routing protocol. Since the proposed algorithm does not require any assumption such as particular topologies and homogeneous networks in which every router has the identical number of radio modules and available channels, it can be easily adopted to real networks.

II. WIRELESS NETWORK PROBLEMS IN THE IEEE 802.11 PROTOCOL

In this section, we first describe the system environment of the IEEE 802.11 protocol and introduce three well-known problems – *hidden terminal*, *exposed terminal*, and *co-channel interference* problems which cause significant degradation of the network performance.

We assume that all routers (nodes) are equipped with half-duplex multi-radio interfaces and have identical signal ranges. We consider following three types of signal ranges to investigate wireless network problems.

- Transmission range(R_t): the range within which nodes can interpret signals so that they receive or overhear packet transmissions.
- Interference range(R_i): the range within which nodes can suffer collisions due to interference.
- Carrier Sensing range(R_s): the range within which nodes can sense the signal.

Previously, the relation among the carrier sensing range, the transmission range, and the interference range in typically employed IEEE 802.11 radio modules was studied [7], [8].

$$R_t < R_i = 1.78R_t < R_s = 2.2R_t$$

We use these relations of signal ranges to formulate the hidden terminal, exposed terminal, and interference problems.

If a transmitter r_t sends a packet to a receiver r_r and at the same time another transmitter r'_t sends data to another receiver r'_r , the transmitters r_t and r'_t should be apart at least $2.2R_t$ from each other. If r_r or r'_r is within R_i of r'_t or r_t respectively, the transmission is disturbed by the non-associated transmitter. As illustrated in Fig. 1(a), the transmission from r_t to r_r is broken by the transmission from r'_t to r'_r . Thus, we define (r_t, r_r) as a hidden link of (r'_t, r'_r) when $d(r_t, r_r) \leq R_t$, $d(r'_t, r_r) \leq R_i = 1.788R_t$, and $d(r_t, r'_t) > R_s = 2.2R_t$. In this case, RTS/CTS handshaking mechanism is not applicable because the transmitter r'_t cannot sense a RTS signal of the transmitter r_t and also cannot interpret a CTS signal of the receiver r_r . This extended version of the hidden terminal problem is also called a *distance terminal problem* [9].

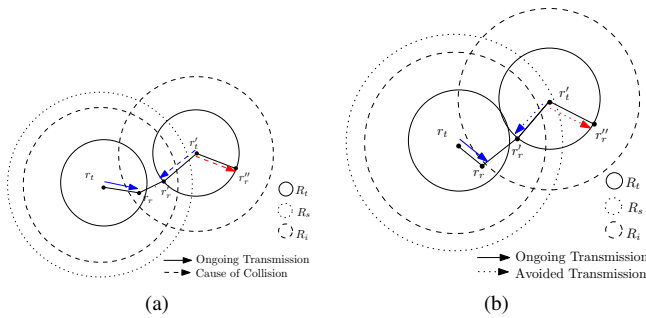


Fig. 1. (a) Hidden terminal problem. (b) Exposed terminal problem.

In our scheme, the exposed terminal problem arises when two transmitters r_t and r'_t are within the sensing range and each of the corresponding receiver r_r and r'_r is not in the

interference range of the non-associated transmitters r'_t and r_t , respectively as shown in Fig. 1(b). We define (r_t, r_r) as the exposed link of (r'_t, r'_r) when $d(r_t, r_r) \leq R_t$, $d(r'_t, r_r) \leq R_t$, $d(r'_t, r_r) > R_i = 1.788R_t$, and $d(r_t, r'_t) \leq R_s = 2.2R_t$.

Indeed, the hidden terminal problem is also caused by the interference at the receiver. In this paper, to distinguish the interference problem from the hidden terminal problem, we only consider the interference detectable by the transmitter. Thus, the interference problem has the following conditions: $d(r_t, r_r) \leq R_t$, $d(r_t, r'_t) \leq R_s$ and $d(r_r, r'_t) \leq R_i$.

III. WEIGHTED CONFLICT MODEL

Let $G_C(V_C, E_C)$ be a communication graph where $V_C = \{r_1, r_2, \dots, r_n\}$ is a set of routers and E_C is a set of communication links. If r_j is located within a transmission range of r_i , there exists a communication link $(r_i, r_j) \in E_C$. Since we assume that all routers have identical transmission ranges, a communication graph is represented as an undirected graph. A communication graph G_C is called *connected* if every pair of routers has a routing path. We assume that a deployed mesh network is connected and a routing protocol establishes a minimum hop count routing path. On the communication model, hop counts are commonly exploited as a distance rather than a Euclidean distance because it is very hard to measure the exact Euclidean distance between two routers and moreover it reflects the communication delay. Since we investigate conflicts among communication links, we define *k-hop links* as two edges whose minimum hop path passes k routers excluding two end routers. If two edges are adjacent, having one shared vertex, it is 1-hop links.

Ideally, if we knew the topology of the network including coordinates of routers, we can produce the precise conflict graph. However, without the knowledge of locations, we are able to be sure of the following three arguments:

- 1-hop links are only affected by interference not by hidden or exposed terminal problem.
- If 2-hop links are affected by hidden or exposed terminal problem, 3-hop links including them also affected by the hidden or exposed terminal problem.
- Up to 3-hop links, they suffer from at least one problem among the interference problem, hidden terminal problem, and exposed terminal problem.

The first two claims are obvious. We prove the third claim simply with the exposed terminal problem and the interference problem. At 1-hop links, it is obvious that the interference problem occurs when two end routers send a packet to a common receiver. At 2-hop links of which path consists of 4 routers, $r_1, \dots, r_4$, r_2 is obviously within a sensing range of r_3 . When r_4 sends a packet to r_1 and simultaneously r_3 sends a packet to r_4 , those two transmissions suffer from either the exposed terminal problem or the interference problem. At 3-hop links of which path consists of 5 routers, $r_1, \dots, r_5$, two transmissions r_2 to r_1 and r_4 to r_5 have the same problem because r_2 is still within a sensing range of r_4 . Consequently, we can guarantee that 1-hop, 2-hop and 3-hop links are

influenced by at least one of the hidden terminal, exposed terminal, and co-channel interference problems. Based on these observations, we construct a conflict graph. Given a communication graph $G_C(V_C, E_C)$, we define a *Weighted Conflict Graph* $G(V, E)$. Each link on a communication graph becomes vertices on the weighted conflict graph, $V = E_C$. Edges on the weighted conflict graph are defined as

$$E = \{(l_i, l_j) \mid l_i \text{ and } l_j \text{ are within 3-hop where } l_i, l_j \in V\}.$$

Weight of each edge represents how critical each conflict is. It is likely that 1-hop links are related to the interference problem, 2-hop links are related to the hidden terminal problem, and 3-hop links are related to the exposed terminal problem mostly if the routers are well distributed. Thus, the weight of each edge is assigned by link distance.

$$w((l_i, l_j)) = \begin{cases} \alpha & \text{if } l_i, l_j \text{ are adjacent,} \\ \beta & \text{if } l_i, l_j \text{ are 2-hop links,} \\ \gamma & \text{if } l_i, l_j \text{ are 3-hop links.} \end{cases}$$

Fig. 2(a) and Fig. 2(b) show the weighted conflict model corresponding to the communication model.

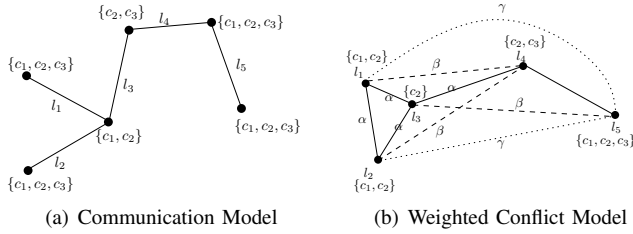


Fig. 2. A communication graph with channel lists and the corresponding weighted conflict graph.

IV. CONFLICT-AWARE CHANNEL ASSIGNMENT

In this section, we present how to assign channels to each router to reduce the conflicts. We define the problem *Max list-Cut problem* which are closely related to the channel assignment and propose the approximation algorithm to resolve the channel assignment problem.

A. Problem Statement

Since we design the weighted conflict model, we can avoid the conflicts by assigning channels differently to all individual links. However, it is not realistic to assign all different channels to links because each router probably equips a limited number of radio modules as well as the number of available channels is restricted. Therefore, we first consider an available channel set of each link. On the communication graph, the available channel set of the link consists of common channels of two end routers of the link. Accordingly, on the weighted conflict graph, each vertex has the same set of available channels as the corresponding link on the communication graph as shown in Fig. 2(a) and Fig. 2(b).

$$L(v) = L(r_i) \cap L(r_j) \text{ where } v = (r_i, r_j) \in V.$$

We now define the Max list-Cut problem. Given an undirected graph $G(V, E)$ with a partition list of each vertex $L(v)$ for $v \in V$ and weight of each edge $w(e)$ for $e \in E$, the Max list-Cut problem is defined as

$$\text{Compute } c(v) \in L(v) \text{ to maximize } \sum_{e \in X} w(e)$$

$$\text{where } X = \{(u, v) \mid c(u) \neq c(v), (u, v) \in E\}.$$

The objective of the Max list-Cut problem is to maximize the total weight of edges whose two end vertices belong to different partitions. The Max list-Cut problem is similar to the *Max k-Cut* problem which is a well-known problem that asks to divide vertices of a given graph into k partitions such that the total weight of edges crossing different partitions is maximized. The Max list-Cut problem is indeed a generalized version of a *Max k-Cut* problem because the Max list-Cut problem is reduced to the Max k -Cut problem if all vertices have the identical partition list of size k in the Max list-Cut problem. The Max k -Cut problem is known to be NP-hard.

B. Approximation Algorithm

In this section, we propose a simple greedy approximation algorithm for the Max list-Cut problem with performance guarantees at least 2.

Algorithm: Greedy Approximation GA

Input: $G(V, E)$ with $L(v)$ for $v \in V$ and $w(e)$ for $e \in E$

Output: $c(v)$ maximizing total weight of crossing edges

- 1: $P_i = \emptyset$ for all partition i
- 2: Add $v \in V$ to P_i where $L(v) = \{i\}$
- 3: Delete all vertices with $|L(v)| = 1$ from V
- 4: **for all** $u \in V$ **do**
- 5: **for all** partition P_i in $L(u)$ **do**
- 6: $W_{P_i}(u) = \sum w(e)$ where $e = (u, v), v \in P_i$
- 7: **end for**
- 8: Add u to P_i where $i = \arg \min_{i \in L(u)} W_{P_i}(u)$
- 9: **end for**
- 10: Assign $c(v) = i$ where $v \in P_i$ for all v

Fig. 3. Algorithm: Greedy Approximation Algorithm

Given a weighted graph with a partition list on each vertex, the proposed algorithm GA partitions every vertex to maximize the total weight of crossing edges as described in Fig. 3. GA consists of two steps. At the first step (line 2-3 in Fig. 3), GA seeks vertices which have partition lists of size 1. In this case, the vertices should be assigned to its own available partition to uphold the connectivity. At the second step (line 4-9 in Fig. 3), we choose a vertex u one by one and assign greedily to a partition in which u increases minimally the weights of edges connecting to the vertices inside the partition.

Theorem 1: GA assigns all vertices to partitions with 2-approximation ratio in $O(|E_C|^2)$ time.

Proof: We consider a set S_1 of vertices which are assigned at the first step. Let $G_{S_1} = (V_{S_1}, E_{S_1})$ be a subgraph where $V_{S_1} = S_1$ and $E_{S_1} = \{(u, v) \in E \mid u, v \in V_{S_1}\}$. Let $W_{in}^{S_1}$ be the total weight of edges whose ends are in the same partition in G_{S_1} . Let $W_{out}^{S_1}$ be the total weight of edges across different partitions in G_{S_1} .

Now, we consider the second step. Let u_i be the i th vertex partitioned at the second step. Let $G_{S2}^i = G_{S2}^{i-1} \cup (u_i, E_i)$ where $E_i = \{(u_i, v) \in E | v \in G_{S2}^{i-1}\}$ and $G_{S2}^0 = G_{S1}$. We consider the edges included in G_{S2} after u_i is partitioned. Let w_{in}^i be the total weight of edges in E_i whose ends are in the same partition. Let w_{out}^i be the total weight of edges in E_i whose ends are not in the same partition. Since GA assigns u_i to the partition in which the total weight of edges newly included is minimized, we have

$$w_{in}^i \leq \frac{1}{|L(u_i) - 1|} w_{out}^i.$$

Let $m = \max(\min_{u_i \in V \setminus V_{S1}}(|L(u_i)|), 2)$. Indeed, any vertex at the second step has a partition list of size at least 2. If we sum up values for all the vertices at the second step, we have

$$W_{in}^{S2} = \sum_{u_i \in V \setminus V_{S1}} w_{in}^i \leq \frac{1}{m-1} \sum_{u_i \in V \setminus V_{S1}} w_{out}^i = W_{out}^{S2}.$$

Now, we have the following inequality.

$$W_{in}^{S2} + W_{out}^{S2} + W_{out}^{S1} \leq \frac{m}{m-1} W_{out}^{S2} + \frac{m}{m-1} W_{out}^{S1}.$$

The total weight of edges W is equal to $W_{in}^{S1} + W_{out}^{S1} + W_{in}^{S2} + W_{out}^{S2}$, so $W_{in}^{S2} + W_{out}^{S2} + W_{out}^{S1} = W - W_{in}^{S1}$. Since the total weight OPT of edges across partitions by the optimal algorithm is always less than or equal to $W - W_{in}^{S1}$, we have

$$OPT \leq W - W_{in}^{S1} \leq \frac{m}{m-1} (W_{out}^{S1} + W_{out}^{S2}).$$

Since the total weight ALG of edges across partitions by the proposed algorithm is $W_{out}^{S1} + W_{out}^{S2}$,

$$OPT \leq \frac{m}{m-1} ALG.$$

Since $m \geq 2$, even if $\min_{v \in V} |L(v)| = 1$, we have the performance guarantee 2.

The number of the elements of all the partition is at most $|V|$, so time complexity is $O(|V|^2) = O(|E_C|^2)$.

Since all vertices belong to one of the partitions in their partition list as a result of the proposed algorithm, we can assign corresponding channels to every communication link in the communication graph. Consequently, the algorithm preserves the network topology.

V. SIMULATION RESULT

We evaluated the performance of the proposed algorithm GA by simulations using NS3 simulator [10]. We deployed wireless nodes in various topologies and randomly chose 5 pairs of sources and sinks. Each source sends the UDP packet sized of 1024byte and we count the packets successfully transmitted. OLSR was used as a routing protocol. We ran each simulation in 100 seconds. We adjust the transmit power as the transmission range, interference range, and carrier sensing range are set to 100m, 180m, and 220m respectively. We also assume that the networks is homogeneous and at most 12

orthogonal channels are available. The rest of the simulation settings follows 802.11 standards provided by NS3.

In our simulation, we set α , β , and γ to 1, 2, and 2, respectively, since 1-hop links are only associated with the interference problem. We devise a greedy heuristic algorithm GH for the comparisons since there have not been algorithms aiming the hidden terminal, exposed terminal and interference problems together. Similar to a common channel assignment [11], GH assigns unused channels greedily to the edges of the communication graph one by one to avoid conflicts of incident edges as long as unused channels are left. Otherwise, GH assigns channels to edges at random.

We show the network performance by the number of the available channels. We also investigate the impact of the RTS/CTS mechanism. We assume that 100 nodes are positioned in a 10 by 10 square lattice with a side length of 90m. Fig. 4(a) shows the average throughput of sink nodes as varying the number of available channels up to 12. Networks in all cases have a tendency to acquire the higher throughputs as the number of available channels increases. Since we designed that GH assigns channels to each link to avoid collisions as much as possible among its neighboring links on the communication graph, GH also provides high performance when it has a larger number of channels. However, GA provides higher performance than GH since GH is not able to handle the hidden/exposed terminal problems appearing through the multi-hop neighbors. The performance with RTS/CTS seems to be lower than that without RTS/CTS because RTS/CTS requires additional control overhead. Thus, we disabled the RTS/CTS mechanism in the rest of the simulation.

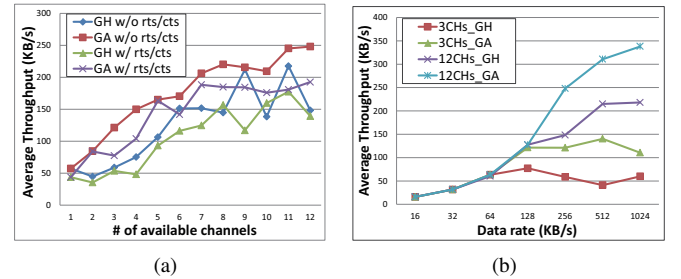


Fig. 4. Network performance in a square lattice: (a) average throughput with the various number of available channels (b) average throughput with different data rate.

Fig. 4(b) shows the network performance with various data rate in the same topology above. We double the data rate of each source node up to 1024KB/s from 16KB/s. We set the number of available channels to 3 and 12. With the lower data rate, almost all packets are successfully transmitted in all cases since there barely occur the simultaneous transmissions. On the other hand, in the highly congested network, GA shows outstanding performance. At the data rate 256KB/s, GA with 12 channels still achieves 96.88% packet success rate. As the network traffic increases, GA with the larger number of available channels enlarges the gap of network performance.

Fig. 5 shows the simulation results in various topologies. We use three different topologies: square lattice, triangular lattice,

and chain. We put 100 nodes 10 by 10 at a square lattice and a triangular lattice with three different side lengths: 50m, 70m, and 90m. In a chain topology, 25 nodes are placed with three different lengths: 50m, 70m, and 90m. We compare the performance of GA with GH when 3 and 12 channels are available. GA with 12 available channels results better throughputs in all cases. In some case, GH with 12 channels also provides similar performance to GA, however, the performance of GH highly depends on the topology settings.

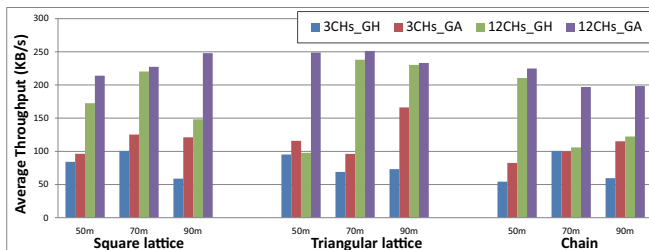


Fig. 5. Network performance in various topologies.

VI. CONCLUSION

In this paper, we propose the channel assignment scheme to improve the degradation of network performance caused by the hidden terminal, exposed terminal, and co-channel interference problems in multi-radio multi-channel WMNs. Since the communication, interference, carrier sensing ranges are all different in the basic 802.11 protocol, these problems are related to not only adjacent links but also the multi-hop links. We first investigate the conditions in which each problem can occur and then design the weighted conflict model which represents possible conflicts caused by those problems. To the best of our knowledge, this is the first approach considering all three problems together. We newly define *Max list-Cut* problem to solve the channel assignment problem on the weighted conflict model and present the approximation algorithm with approximation ratio 2. Since the Max list-Cut problem is a generalized version of the Max *k*-Cut problem, it can be used in various other problems. We show that the proposed channel assignment achieves high performance in various topologies by the simulation.

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