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Partially Overlapping Channel Assignment Based on "Node Orthogonality" for 802.11 Wireless Networks

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***Abstract*—In this study, we investigate the problem of partially overlapping channel assignment to improve the performance of 802.11 wireless networks. We first derive a novel interference model that takes into account both the adjacent channel separation and the physical distance of the two nodes employing adjacent channels. This model defines "node orthogonality", which states that two nodes over adjacent channels are orthogonal if they are physically sufficiently separated. We propose an approximate algorithm MICA to minimize the total interference for throughput maximization. Extensive simulation study has been performed to validate our design and to compare the performances of our algorithm with those of the state-of-the-art.**

I. Introduction

The increasing popularity of Wireless Local Area Networks (WLANs) has led to a dramatic increase in the density of Access Points (APs) in many real-world applications. High node density results in strong interference and poor network performance [1]. Thus, multichannel communications has been proposed as a viable approach to mitigate such problems [2].

Nevertheless, mainstream research focuses on assigning non-overlapping channels to interfering nodes [2]–[5]. Under such a consideration, two interfering nodes can simultaneously transmit without interfering with each other only if their channels are orthogonal. However, because the number of non-overlapping channels is very limited (802.11b/g defines only 3 orthogonal channels), interference can not be completely eliminated in practical settings.

Recent studies indicate that utilizing partially overlapping channels to facilitate interference mitigation can improve the full-range channel utilization and the network throughput [6]–[8]. These advantages are attributed to the fact that *partially overlapping channels do not cause interference with each other if the two nodes (i.e., the transmitter of one channel, and the receiver of the other adjacent channel) are sufficiently physically separated*. Unfortunately, this property is not fully investigated as it should be. The interference models in [6], [7] only consider the channel separation. Though Ding et al. [8] present a weighted conflict graph by taking into account both the channel separation and the physical distance, its interference indicator is a 0-1 variable that cannot accurately reflect the degree of interference from different adjacent channels with different physical distances.

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In this paper, we investigate channel allocation by considering all channels equally. We first propose a novel *Interference Factor* I_c that captures the degree of interference between two channels at different positions. This interference factor is employed to formulate an interference minimization problem for partially overlapping channel assignment to maximize the aggregated network throughput. Also, an approximate algorithms, MICA, to tackle the optimization problem via relaxation and rounding, is proposed. MICA, which stands for *Minimum Interference for Channel Allocation*, minimizes the sum of the weighted interference.

The rest of the paper is organized as follows. The network and interference models are described in Section II. In Section III, we investigate the problem of interference minimization and throughput maximization. Our algorithm is proposed with details in Section IV. After reporting our performance evaluation in Section V, we conclude this paper in Section VI.

II. Network and Interference Models

A. Network Model

In this paper, we consider an IEEE 802.11-based WLAN in which a user associates to the AP with the highest Received Signal Strength Indication (RSSI). An AP together with its associated users form a Basic Service Set (BSS). All nodes belonging to the same BSS operate on the same channel, i.e., the AP's channel. Since APs in close neighborhood may be assigned partially overlapping channels, BSSs might interfere with each other.

The objective of this study is to investigate adjacent channel assignment for downlink network performance maximization. Note that we choose to focus on downlink, in which data is sent by APs to users, because it carries the dominate traffic for many real-world applications such as in social networks [1], [4]. Adjacent channel assignment to maximize uplink performance will be investigated in our future research. For downlink, the experienced interference of an AP depends on the received power from other APs. There are three main factors that affect the received power from an interfering AP:

(i) the transmit power of the interfering AP, (ii) the channel separation, and (iii) the physical distance between the two APs.

For simplicity, we assume that all APs transmit at the same power p. But the proposed interference model and algorithms can be easily extended to the case when the transmit powers vary.

The IEEE 802.11 standard defines a set of discrete channels for radios to operate on. The transmitter should follow the Transmit Spectrum Mask defined in the standard when allocating a power to each frequency in the channel band, with the center frequency of the channel band receiving the highest power. At the receiver side, a band-pass filter, again defined by the standard, is employed to capture the transmitted power. To characterize their relationship, we introduce the concept of *channel adjacency degree*, which is defined as the amount of transmit power covered by the receiver band-pass filter [7]:

$$\phi(c_i, c_j) = \int_{-\infty}^{+\infty} S_t(f) S_r(f - \tau) df,$$

where c_i and c_j are the transmit and receive channel numbers, respectively, $S_t(f)$ is the transmit power distribution across the frequency spectrum, $S_r(f)$ is the band-pass filter's frequency response, and τ is the channel separation in MHz.

B. Interference Model

Since $\phi(c_i, c_j)$ only considers the channel separation, it is not the right parameter to characterize interference. To introduce our interference model for partially overlapping channels, we start from a simple case that consists of AP i transmitting at channel c_i and AP j receiving at channel c_j. Let N_0 be the noise experienced by AP j, and γ_{th} be the SINR threshold for successful communications. Then, to correctly decode a signal, the following condition must be held:

$$\gamma_{th} < \frac{\phi(c_i, c_j) p d_{ij}^{-\alpha}}{N_0}, \tag{1}$$

where p is the transmit power, d_{ij} is the physical distance between AP i and AP j, and α is the shadowing factor ranging from 2.0 to 5.0 [9]. Note that this inequality indicates that a transmission made on a channel c_i can be correctly received at a partially overlapping channel c_j as long as the received signal is strong enough. Based on this observation, we define the *adjacent channel transmission range* between c_i and c_j, denoted by $D_t(c_i, c_j)$, as follows:

$$D_t(c_i, c_j) = \sqrt[\alpha]{\frac{p\phi(c_i, c_j)}{\gamma_{th} N_0}}. \tag{2}$$

Correspondingly, we define

$$D_i(c_i, c_j) = \beta(c_i, c_j) D_t(c_i, c_j) \phi_(c_i, c_j)^{-\frac{1}{\alpha}}$$

to denote the *adjacent channel interference range* between channels c_i and c_j, where $\beta(c_i, c_j)$ is the coefficient characterizing the impact of channel separation on the interference range, and $D_t(c_i, c_j)\phi_(c_i, c_j)^{-\frac{1}{\alpha}}$ represents the transmission range between two nodes in the same channel. Ding *et al.* [8] conduct an experimental study to obtain the settings of $\beta(c_i, c_j)$, for different channel separations under different AP transmission bit rates in 802.11b networks.

Now, we are ready to define our *interference factor*, which takes both the physical distance separation and the channel separation into account. For two APs i and j separated by a physical distance of d_{ij}, the normalized interference factor between i and j, denoted by $I_c(i, j)$, is mapped to a real number in $[0, 1]$ and defined by Eq. (3):

$$I_c(i, j) \;\; = \;\; 1 - \frac{\min\{d_{ij}, D_i(c_i, c_j)\}}{D_i(c_i, c_j)}. \tag{3}$$

Especially, we define that $I_c(i, j) = 0$, if $D_i(c_i, c_j) = 0$. From Eq. (3), it can be observed that $I_c(i, j)$ has the following properties: (i) For a fixed physical distance d_{ij}, $I_c(i, j)$ monotonically decreases with the channel separation. (ii) For a fixed channel separation, $I_c(i, j)$ monotonically decreases with the physical distance. (iii) $I_c(i, j)$ is a real number in $[0, 1]$. A larger value indicates more serious interference. When $I_c(i, j) = 0$, AP i and j can transmit simultaneously without interfering with each other. Note that properties (i) and (ii) of $I_c(i, j)$ are consistent with the observations obtained from real-world experiments [7], [10]. In other words, we use $I_c(i, j)$ to summarize the observations in [7], [10] mathematically. The property (iii) describes the degree of interference of different node pairs. $I_c(i, j)$ is unitless, and is normalized to the range $[0, 1]$. Therefore it can be used to compare the interference degree of different node pairs, no matter which channels the transmitter and receiver are using.

Also note that $I_c(i, j)$ can be used to define "node orthogonality". Traditionally, orthogonality refers to the independency among channels where two channels are orthogonal if and only if they are non-overlapping. With $I_c(i, j)$, the definition of orthogonality can be extended to nodes: *two nodes are orthogonal if and only if their $I_c(i, j)$ is equal to 0.* Indeed, the focus of this paper is to investigate the node orthogonality for channel assignment to decrease interference and improve performance.

III. Throughput Maximization with Partially Overlapping Channels

A. Problem Formulation

Consider the BSS of AP j operating on channel c_j. The bit rate of a user is determined by its experienced SINR. Let γ_{ij} denote the SINR of user i associated with AP j over c_j. In the partially overlapping channel scenario, we have:

$$\gamma_{ij} = \frac{p d_{ij}^{-\alpha}}{\sum_{k=1}^{N} \phi(c_k, c_j) p d_{ik}^{-\alpha} + N_0}, \tag{4}$$

where the denominator captures the interference experienced by user i caused by APs working at channel c_k. The corresponding bit rate r_{ij} can be calculated based on Shannon's capacity theory: $r_{ij} = B \log_2(1 + \gamma_{ij})$, where B is the channel bandwidth.

Let $b_i (i = 1, 2, \ldots, M)$, be the effective bandwidth of user i. The bandwidth of user i obtained from AP j is denoted by b_{ij}. Let x_{ij} be the binary association coefficient of user i and AP j with $x_{ij} = 1$ if and only if the user i is associated with AP j. Note that x_{ij} is a constant since a user selects the AP with the strongest RSSI from all its available APs. Therefore, the user bandwidth is determined by

$$b_i = \sum_{j=1}^{N} x_{ij} b_{ij}. \quad (5)$$

For a given user-AP association $\{x_{ij}\}$, our goal is to maximize the aggregated throughput in the network by allocating partially overlapping channels to APs. The objective function is defined as $\sum_{i=1}^{M} b_i = \sum_{i=1}^{M} \sum_{j=1}^{N} x_{ij} b_{ij}$, where b_{ij} is calculated by the following equation:

$$b_{ij} = \begin{cases} r_{ij}, & \text{if } r_{ij} = \max\limits_{k \in U_s(j)} \{r_{kj}\}, \\ 0, & \text{otherwise}, \end{cases} \quad (6)$$

with $U_s(j)$ being a user set consisting of all users associated with AP j. Note that Eq. (6) indicates that to obtain the maximum aggregated throughput, only the user with the highest bit rate is allowed to communicate in the multi-rate environment.

For this optimization problem we need to consider the following two constraints: (i) Each AP is allowed to access only one channel. Let $Y_{N \times K} = \{y_{jh}\}$ be a binary matrix indicating the channel assignment, where $y_{jh} = 1$ if and only if AP j transmits over channel $h (h = c_j)$. With this notation, b_i can be expressed by $b_i(Y)$. (ii) The SINR at user i must be at least $\gamma_{th} > 0$, i.e., $\gamma_{ij} \geq \gamma_{th}$ for $j = 1, 2, \cdots, N$.

In summary, mathematically the partially overlapping channel allocation for throughput maximization can be formulated by the following optimization problem, with y_{jh} as the set of variables to be determined:

$$\max \quad \sum_{i=1}^{M} b_i(Y) \quad (7a)$$

$$\text{s.t.} \quad \sum_{h=1}^{K} y_{jh} = 1, 1 \leq j \leq N, \quad (7b)$$

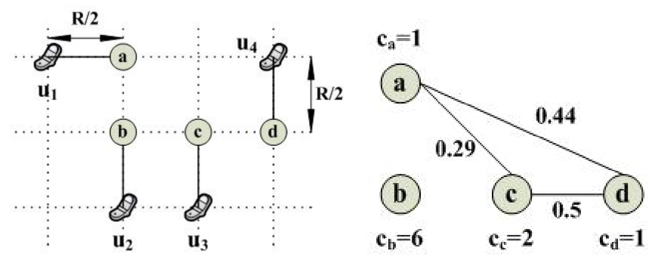
$$\sum_{j=1}^{N} x_{ij} \gamma_{ij} \geq \gamma_{th}, 1 \leq i \leq M, \quad (7c)$$

$$y_{jh} \in \{0, 1\}, 1 \leq j \leq N, 1 \leq h \leq K. \quad (7d)$$

For simplicity, the above optimization program is referred as the Original Channel Allocation Problem (**O-CAP**). Eq. (7a) is our objective function with each b_i calculated by Eq. (5). The constraint (7b) shows that an AP is allowed to access only one channel; the constraint (7c) indicates that the SINR between user i and AP j must meet the communication requirement; and the constraint (7d) specifies the range of the variable y_{jh}.

B. Throughput vs. Interference

In this subsection, we study the relationship between throughput and interference when partially overlapping channels are employed. Given a channel assignment, we can construct a *weighted interference graph* $G(V, E)$ such that each AP corresponds to a node in V and an edge with a weight $I_c(i, j)$ between two nodes i and j exists if and only if $i, j \in V$ and $I_c(i, j) > 0$. An example is shown in Fig. 1(a), in which four APs $\{a, b, c, d\}$ and four users $\{u_1, u_2, u_3, u_4\}$ form an 802.11 wireless network with the solid edges indicating the user-AP association and $R = \sqrt[4]{\frac{p}{\gamma_{th} N_0}}$. All AP transmit with a single data rate of 11 Mbps and a unique transmit power p. Each AP is placed on a grid point, and the grid is a square with a side length of $\frac{R}{2} (R = \sqrt[4]{\frac{p}{\gamma_{th} N_0}})$. Fig. 1(b) illustrates the weighted interference graph for the channel assignment $c_a = 1$, $c_b = 6$, $c_c = 2$, and $c_d = 1$, with the weights computed by Eq. (3).



(a) An example of networks. (b) The weighted interference graph.

Fig. 1. An example of the construction of the weighted interference graph.

Based on the weighted interference graph, we construct the following optimization problem (Eq. (8)) to minimize the sum of the weighted interference, which is referred as **Min-Ic**. Note that **Min-Ic** is simpler compared to **O-CAP** as the minimum SINR requirements of the users are removed.

$$\min \quad \sum_{j=1}^{N} \sum_{k=1}^{N} w_{kj} I_c(k, j) \quad (8a)$$

$$\text{s.t.} \quad \sum_{h=1}^{K} y_{jh} = 1, 1 \leq j \leq N, \quad (8b)$$

$$y_{jh} \in \{0, 1\}, 1 \leq j \leq N, 1 \leq h \leq K, \quad (8c)$$

where $w_{kj} = \sum_{i=1}^{M} x_{ij} (\frac{d_{ik}}{d_{jk}})^{-\alpha}$.

From Eqs. (2) and (3), it can be observed that maximizing Eq. (7a) is equivalent to minimizing Eq. (8a). In other words, for a given user-AP association $\{x_{ij}\}$, **O-CAP** and **Min-Ic** are equivalent. Thus, we can solve a relatively simpler problem, i.e., **Min-Ic** in stead of the more complex **O-CAP** to compute the channel assignment for throughput optimization.

The example illustrated in Fig. 1 is used to validate the relationship between the aggregated throughput and the sum of the weighted interference. Since each AP has only one user, the aggregated throughput is the sum of the bit rates of all users. There are six available partially overlapping channels, with only two non-overlapping ones, i.e., 1 and 6. The optimal channel assignment by **Min-Ic** and the corresponding total throughput and total interference are reported in the first row of Table I. For comparison purpose, we also provide the throughput and total interference of other feasible channel assignment solutions.

TABLE I
THE SOLUTION OF MIN-IC

Solution	Assignment	Throughput(b/s)	Interference
Optimal	(6,2,4,1)	24.06	0.00
Feasible 1	(1,6,1,6)	16.67	1.15
Feasible 2	(1,1,1,1)	7.33	3.84

IV. APPROXIMATE ALGORITHM FOR MIN-IC

In this section, we propose a centralized approximate algorithm termed **M**inimum **I**nterference for **C**hannel **A**llocation (**MICA**), for the problem **Min-Ic**. **MICA** is executed by placing a network manager to collect the necessary information based on which to calculate the channel assignment. It consists of three steps as shown in Alg. 1.

Algorithm 1 MICA

1: Obtain the fractional solution $\{y^f_{jh}\}$ by solving a relaxed optimization.
2: Obtain the integral solution $\{y_{jh}\}$ by a rounding process.
3: Assign the channels to APs

The basic idea is to relax the 0-1 binary variable y_{jh} such that a fractional optimal solution can be found in polynomial time. Then we use a rounding process to obtain an integral solution based on which we assign adjacent channels to all APs. The details are elaborated in the following two subsections.

A. Relaxation of Min-Ic

The first step is to relax the binary variable y_{jh} such that $0 \le y_{jh} \le 1$. That is, an AP is allowed to access multiple channels. In such a scenario, AP j selects channel h if $y_{jh} > 0$. Let $I^f_c(k, c_k, j, c_j)$ be the interference between AP k in channel c_k and AP j in channel $c_j (c_j = h)$. Thus, the total interference between AP k and j is:

$$I_c(k, j) = \sum_{h=1}^{K} y_{jh} \sum_{c_k=1}^{K} I^f_c(k, c_k, j, h), \tag{9}$$

where $I^f_c(k, c_k, j, h) = 1 - \frac{\min\{d_{kj}, D_i(c_k,h)\}}{D_i(c_k,h)}$.

Substituting the $I_c(k, j)$ in Eq. (8) with that in Eq. (9), we obtain the corresponding relaxed optimization problem that is referred as **RMin-Ic**:

$$\min \quad \sum_{j=1}^{N}\sum_{k=1}^{N} w_{kj} \sum_{h=1}^{K} y_{jh} \sum_{c_k=1}^{K} I^f_c(k, c_k, j, h) \tag{10a}$$

$$\text{s.t.} \quad \sum_{h=1}^{K} y_{jh} \le 1, 1 \le j \le N, \tag{10b}$$

$$y_{jh} \in [0, 1], 1 \le j \le N, 1 \le h \le K. \tag{10c}$$

This problem can be solved in polynomial time. The fractional optimal solution to the problem **RMin-Ic** is denoted by $I(Y^f)$.

B. Rounding for Min-Ic

In this step, we use the rounding algorithm proposed in [11] to obtain an integral assignment matrix Y. The main idea is to construct a weighted bipartite graph based on the fractional assignment and find the minimum-weight matching for the problem **Min-Ic**. First, we introduce a definition to be used in the rounding process.

Definition 1: The experienced interference of AP j on channel h is defined as $I_{jh}(a) = \sum_{k=1}^{N} \sum_{c_k=1}^{K} w_{kj} I^f_c(k, c_k, j, h)$, where $w_{kj} = \sum_{i=1}^{M} x_{ij} (\frac{d_{ik}}{d_{jk}})^{-\alpha}$.

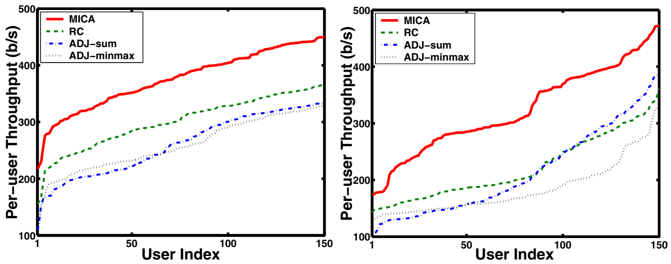
The detail of the rounding scheme is as follows. First, we construct a bipartite graph $G_B(Y) = (A, V, E)$, where the set A represents the APs in the network, and the set V consists of the channels denoted by $V = \{v_{hs} : h = 1, \ldots, K, s = 1, \ldots, S_h\}$, with $S_h = \lceil \sum_{j=1}^{N} y^f_{jh} \rceil$. This means that each channel may have multiple nodes in V. The edges in $G_B(Y)$ are constructed in the following way. For each channel h, we renumber the APs according to their non-increasing experienced interference $I_{jh}(a)$. If $S_h \le 1$, for each $y^f_{jh} > 0$, add an edge $e(a_j, v_{h1})$ to E, and set $y^f(a_j, v_{h1}) = y^f_{jh}$. Otherwise, find the minimum index j_s such that $\sum_{j=1}^{j_s} y^f_{jh} \ge s$. For $j = j_{s-1} + 1, \ldots, j_s - 1$ and $y^f_{jh} > 0$, add an edge $e(a_j, v_{hs})$ and set $y^f(a_j, v_{hs}) = y^f_{jh}$. For $j = j_s$, add the edge $e(a_j, v_{hs})$ and set $y^f(a_j, v_{hs}) = 1 - \sum_{j=j_{s-1}+1}^{j_s-1} y^f(a_j, v_{hs})$. If $\sum_{j=1}^{j_s} y^f_{jh} > s$, add the edge $e(a_j, v_{h(s+1)})$ and set $y^f(a_j, v_{h(s+1)}) = \sum_{j=1}^{j_s} y^f_{jh} - s$. In such a case, the weight of each edge $e(a_j, v_{hs})$ in E is defined by $I_{jh}(a)$.

Second, we find a minimum-weight matching $M(Y)$ that matches each AP node to a channel node in $G_B(Y)$. For each edge $e(a_j, v_{hs})$ in $M(Y)$, schedule AP j on channel h and set $y_{jh} = 1$. Set other y_{js}'s to be 0. Since the fractional assignment $\{y^f_{jh}\}$ specifies a fractional matching, such a maximal matching does exist and it determines the integral association $\{y_{jh}\}$.

Note that the rounding procedure of Algorithm 1 also completes the third step, i.e., assigning channels to the APs based on the integral solution obtained from the rounding process.

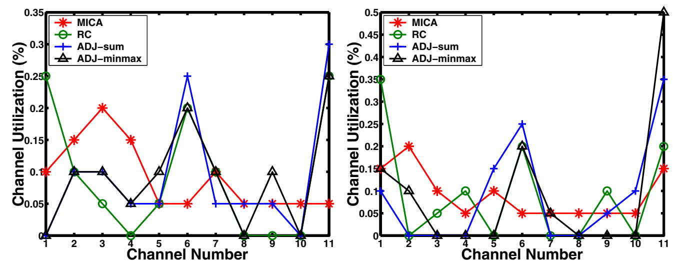
V. SIMULATION

In this section, we evaluate the performance of our proposed algorithm through an extensive simulation study, and compare its performance with those of Randomized Compaction (RC) [7], ADJ-sum, and ADJ-minmax [6], the most relevant research that considers partially overlapping channel assignment. The objectives of ADJ-minmax and ADJ-sum, are to minimize the maximum interference among all interfering APs, and to minimize the sum of the weights on all conflict edges, respectively. RC, on the other hand, intends to minimize the maximum conflict vector that consists of the total number nodes interfering with each user arranged in non-increasing order. RC starts with a random channel assignment and refines the result iteratively.



(a) the uniform case (b) the hotspot case

Fig. 2. The per-user throughput.



(a) the uniform case (b) the hotspot case

Fig. 3. The channel utilization.

Note that all these algorithms are centralized and they are examined according to the following two performance metrics: (i) the per-user throughput; and (ii) the channel utilization ratio, which characterizes the utilization of each available channel and is defined to be the ratio of the number of APs over the channel and the total number of APs.

There are two different scenarios in our simulation, the uniform and the hotspot cases, with both containing 20 APs and 50-250 users. For the uniform case, APs and users are placed uniformly at random in a $1400m \times 900m \times 10m$ region. In the hotspot case, to simulate high interference in the wireless environment, we place users in a certain area with $500m \times 500m \times 10m$, while APs distribute uniformly at random in a $1000m \times 500m \times 10m$ region.

We solve the relaxed non-linear program (Eq. (10)) by LINGO and use QualNet as the simulator. We report our numerical simulation results, which are averaged over 50 runs with each taking 300s simulation time. Since the results are essentially similar, we only report the case with 20 APs and 150 users.

First, the per-user throughput is reported in Fig. 2, with the users sorted by their throughput in increasing order. From Fig. 2, we observe that our algorithm outperforms the other three algorithms in terms of per-user throughput for both network settings. The superiority of our algorithm is attributed to the interference factor I_c, which helps to obtain a more appropriate channel assignment with a more accurate modeling. In summary, we conclude that our algorithm is superior in terms of throughput compared to others when partially overlapping channels are exploited.

Next, we show the utilization of each channel in Fig. 3. It can be seen that in both cases, **MICA** utilizes all channels while RC, ADJ-sum and ADJ-minmax only use a part of them. Furthermore, the variances of the channel utilization produced by our algorithm is smaller than those from others. The essential reason for these two results is that our algorithm allocates channels based on "node orthogonality" which takes into account both the channel separation and the physical distance separation while others assign channels based on the traditional channel orthogonality by only considering the channel separation. This indicates that the "node orthogonality" can help to mitigate interference.

VI. Conclusion

The widespread use of WLAN applications drives a high density deployment of APs, leading to an increase in interference and a decrease in the network performance. In this paper, we study how to mitigate interference and improve the network performance by allocating partially overlapping channels. A novel interference model characterized by the interference factor I_c is introduced, which takes into account both the channel separation and the physical distance separation of the two nodes. Based on this model, we formulate an interference minimization problem and propose a heuristic algorithm **MICA**. Our simulation study indicates that **MICA** outperforms RC, ADJ-sum, and ADJ-minmax in terms of per-user throughput and channel utilization ratio under both the uniform and the hot-spot user deployment patterns.

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