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Network Planning Based on Interference Alignment in Density WLANs

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ABSTRACT In high-density scenarios, wireless local area networks (WLANs) encounter serious interference. Interference alignment (IA) is an effective manner to control interference and improve system capacity in the interference channel. However, interference channels interact with each other in existing network planning manners and the network throughput cannot be improved significantly through the IA. In order to control interference and improve the network throughput more efficiently, we propose a network planning scheme based on the IA in high-density WLANs. The whole network is divided into a plurality of subregions, and neighbor subregions use different channels. Each subregion is considered as an interference channel, and the IA is utilized to control interference in a single subregion. Meanwhile, inter-subregion interference is controlled by channel allocation. The appropriate size of subregions and the optimal channel allocation will be selected according to the principle of maximizing the degree of freedom (DoF) of the whole network. The DoF describes the number of messages transmitted at the same time, therefore, this manner will make high-density WLANs more competitive by improving the average DoF. In the simulations, the proposed network planning manner is compared to the traditional manner in different scales of the WLANs, and the results show that the proposed manner can improve the average DoF in high-density WLANs.

INDEX TERMS Channel allocation, degree of freedom, interference alignment, interference channels, network planning, wireless LAN.

I. INTRODUCTION

Nowadays, Wireless Local Area Networks (WLANs) have been deployed widely. In order to provide seamless services and support a large number of users, Access Points (APs) are usually deployed densely in hotspots such as airports and conference rooms. Unfortunately, high density deployment leads to serious interference. In WLANs, an AP and Stations (STAs) associated with it constitute a Basic Service Set (BSS). Adjacent BSSs usually use non-overlapped channels to avoid interference. In sparse WLANs, co-channel interference can be suppressed very well through channel allocation algorithms. However, in high density WLANs, a large number of APs are in the interference range of each other, and non-overlapped channels are too few to be allocated for the interference avoidance.

Many researches focus on optimizing the channel allocation [1]–[3] and the carrier sensing [4], [5] to reduce co-channel interference in high density WLANs. An optimal channel allocation scheme can reduce interference and improve the network throughput. However, in high density scenarios, there are no enough non-overlapped channels for channel allocation algorithms to make nearby BSSs which are in the interference range of each other use different channels. Carrier sensing helps APs and STAs to avoid collision, but only one of co-channel nodes (i.e., APs and STAs) in the carrier sensing range can transmit in a time slot. In order to improve the throughput of high density WLANs, co-channel interference should be controlled more efficiently.

Interference Alignment (IA) is an effective manner to control interference and improve system capacity in the interference channel [6]. Co-channel BSSs in the interference range of each other comprise an interference channel. Thus, IA can be utilized to control co-channel interference in density WLANs by designing an appropriate IA manner [7].

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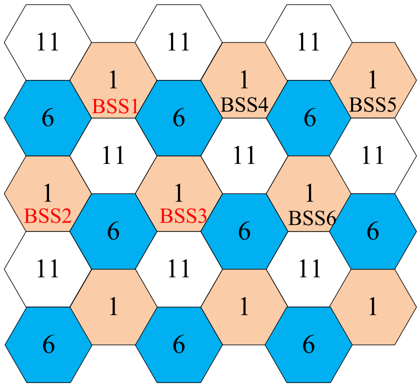

FIGURE 1. A traditional network planning scheme in which neighbor BSSs work on non-overlapped channels.

In existing high density WLANs, adjacent BSSs usually use non-overlapped channels to avoid interference. A typical WLAN working on 2.4GHz is shown as Fig. 1. In a dense WLAN, some nearby co-channel BSSs (e.g., BSS1, BSS2 and BSS3) are in the interference range of each other, and IA can be utilized to control interference. For example, BSS1, BSS2 and BSS3 comprise IA unit 1, and BSS4, BSS5 and BSS6 comprise IA unit 2.

However, BSS1 and BSS4 are also in the interference range of each other. IA unit 1 and IA unit 2 interfere with each other, and they can not transmit at the same time. In this situation, the network performance can not be improved significantly due to the inter-IA-unit interference.

This paper proposes a new network planning scheme to avoid interference among neighbor IA units. In the proposed network planning scheme, the high density WLAN is divided into a plurality of subregions. BSSs in the same subregion use the same channel, and the neighbor subregions use non-overlapped channels to avoid interference. Each subregion can be regarded as an IA unit, and the interference in the subregion could be controlled by IA.

To divide subregions appropriately and allocate optimal channels for these subregions, the Degree of Freedom (DoF) is used. The DoF describes the number of messages which can be transmitted at the same time. Therefore, the average DoF of all BSSs can indicate the throughput of the whole network. And the subregion partition and channel allocation scheme with the largest average DoF should be chosen.

To evaluate the performance of the proposed scheme, we simulate it with different network scales and different network density. The simulation results show that the proposed network planning manner can achieve higher average DoF than the traditional network planning manner by using the appropriate subregion size in high density WLANs.

The main contributions of this paper are summarized as follows:

- We propose a new network planning scheme to avoid interference among neighbor IA units and improve the network performance. The network is divided into a number of subregions. BSSs in the same subregion use the same channel, and the interference in a single subregion is controlled by IA. Meanwhile, the inter-subregion interference is suppressed by the channel allocation.
- To get an appropriate subregion partition and channel allocation scheme, the average DoF is utilized. The DoF describes the number of messages which can be transmitted at the same time. Therefore, the scheme with the largest average DoF should be selected to improve the throughput of the network as much as possible.
- We use the interference graph to calculate the average DoF. In the interference graph, a clique (i.e., a fully connected subgraph) denotes interfered IA units which can not transmit at the same time. And the average DoF can be obtained according to the graph division and the maximal clique algorithm.

The remaining parts of the paper are organized as follows: Section II presents the related work. The system model is given in Section III. Then Section IV describes the proposed network planning scheme in details. And Section V shows the performance evaluation and analyzes the results. Finally, Section VI concludes the paper.

II. RELATED WORK

In high density WLANs, co-channel interference has a great impact on network performance. In order to reduce interference, many researches focus on channel allocation algorithms. Mishra *et al.* [8] processed the channel allocation as the graph vertex coloring problem, in this manner, they allocated different channels for neighbor vertexes and allocated different matrices for edges to reduce interference. In the channel allocation process, co-channel interference can be controlled by maximizing the minimum distance between co-channel APs [9]. Sun *et al.* [10] divided the network into several conflict areas according to the interference range. Tewari and Ghosh [11] proposed a partially overlapping channel assignment algorithm that jointly considers power tuning and channel assignment to maximize the network performance.

Co-channel BSSs interfere with each other, which reduces the efficiency of Carrier Sense Multiple Access (CSMA) and the network throughput. Hua *et al.* [4] analyzed the impact of CSMA in high density scenarios, and chose the lowest captured channel for each user to reduce interference and improve CSMA efficiency. Baid and Raychaudhuri [1] solved the channel chosen problem in high density scenarios by the graph theory. They built a conflict graph according to the CSMA listening range of APs, and allocated channels to maximize the CSMA throughput. Kim *et al.* [5] used a carrier sense threshold adaptation method to improve spatial reuse in WLANs, and then proposed a supplementary Clear Channel Assessment (CCA) method to further enhance network performance by reducing CCA overhead.

Cadambe and Jafar [6] proposed a linear interference alignment scheme. Interference alignment has significant gains in interference channels [12] with the Channel State

Information (CSI). They proved that IA could achieve the optimal DoF in interference channels, and the optimal DoF could achieve K/2 in the K-user interference channel.

In practical applications, CSI at the Transmitter (CSIT) is difficult to be obtained. Fortunately, IA can obtain DoF gains without CSIT, and this type of IA is called Blind Interference Alignment (BIA) [13]–[16]. Since BIA incurs no delay or complexity, it can be easily incorporated into existing communication systems [13]. In order to obtain IA gains, BIA requires additional conditions. In the multiple users interference channel, BIA can be realized when different channels have different coherence time [14]. If the characteristic of antennas can be changed, BIA can also be realized, and this type of antenna is called the reconfigurable antenna [15], [16]. Lu *et al.* [17] proved that the reconfigurable antenna could realize IA in the K-user interference channel, and the whole system could achieve KM/(K+M-1) DoF if there were M regular antennas in each transmitter and one reconfigurable antenna in each receiver. Zhou *et al.* [18] reconsidered the design of BIA for the K-user MISO interference channel and proposed a mode switching scheme for the reconfigurable antenna.

In high density WLANs, co-channel BSSs in the interference range of each other can be regarded as an interference channel, and IA can be used. Oh *et al.* [19] proposed a distributed IA algorithm, and managed the down-link interference through global CSI and the cooperation among nodes. Jin *et al.* [20] proposed an interference management technique for overlapping BSSs in WLANs, and applied opportunistic IA to WLANs. Oh *et al.* [21] proposed an IA functional sequence protocol in IEEE802.11 and evaluated the throughput with the protocol overhead considered.

Existing researches utilize IA to manage interference and increase the DoF in WLANs. The increase of the DoF means that more messages can be transmitted at the same time. Therefore, the throughput of the network will be improved with the increasing of the DoF. However, existing researches do not consider the network planning manner when utilizing IA. In existing high density WLAN channel allocation manners, several IA units interfere with each other. IA units that interfere with each other can not transmit at the same time, therefore, the throughput of the whole network can not be improved significantly in existing network planning manners.

III. NETWORK PLANNING BASED ON INTERFERENCE ALIGNMENT

A. DEGREE OF FREEDOM IN HIGH DENSITY WLANS

In high density WLANs, the distance between a BSS and its nearest co-channel neighbor is shorter than the interference range. In the WLAN shown in Fig. 2, the APs are deployed densely, and there are 3 available non-overlapped channels (i.e., Channel 1, Channel 6 and Channel 11). In this situation, each BSS interferes with some co-channel BSSs which are not adjacent to it.

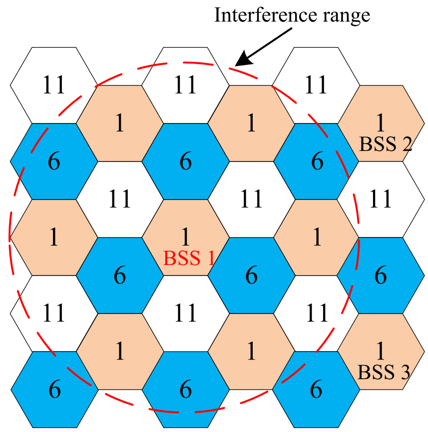

FIGURE 2. **Interference in a traditional WLAN.**

In IEEE802.11, two types of Media Access Control (MAC) layer mechanisms can be used. The first type is the competition-based mechanism (i.e., Distributed Coordination Function (DCF)), and the second one is the allocation-based mechanism (i.e., Point Coordination Function (PCF)). No matter which MAC layer mechanism is used, only one node can access the channel and transmit messages at a single time slot in a BSS. A STA associated with the AP will send messages to the AP when it has the channel accessing chance to transmit. On the other hand, the AP will send messages to one of STAs when it has the channel accessing chance.

Assume that there are k co-channel BSSs in the interference range of each other. Since only a pair of nodes (i.e., the AP and a STA associated with it) can transmit messages at the same time in each BSS, each BSS can be regarded as a pair of nodes. And the k co-channel BSSs constitute a k-user interference channel. If there is no interference management scheme, only one pair of nodes can transmit messages at the same time in the whole interference channel. In other words, the DoF of these co-channel BSSs is 1, and the average DoF of each BSS is $1/k$.

In the high density WLAN with the traditional network planning manner, each BSS interferes with several co-channel BSSs which are in the interference range. As shown in Fig. 2, there are 9 BSSs working on Channel 1. Let's assume that the interference range is 4 times longer than the radius of the BSS. 6 BSSs using Channel 1 interfere with BSS 1, and only BSS 2 and BSS 3 can transmit messages while BSS 1 is transmitting. Thus, it will take 3 time slots to make all BSSs have a time slot to transmit, and the average DoF of these BSSs is 1/3. Similarly, the average DoF of BSSs using Channel 6 and Channel 11 is 1/3 too. Therefore, the average DoF of the whole network is 1/3.

Recall that IA can obtain DoF gains in the interference channel. The average DoF is probably increased by regarding interference channels as IA units and implementing IA in each IA unit.

However, as shown in Fig. 2, in the traditional network planning manner, almost each IA unit interferes with other

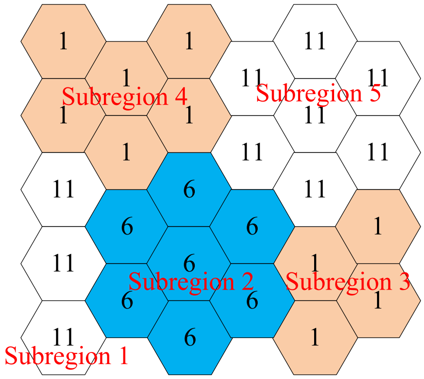

FIGURE 3. An illustration of the subregion network planning.

IA units because neighbor co-channel IA units contain BSSs that are in the interference range of each other. No matter how to divide IA units, each IA unit has at least one co-channel neighbor, and these IA units can not transmit at the same time.

In order to increase the average DoF of the whole network, neighbor IA units should be separated by different physical channels through a new network planning manner.

B. NETWORK PLANNING BASED ON IA AND THE SYSTEM MODEL

In this paper, we propose a network planning manner to separate IA units. The network is divided into several subregions. BSSs in the same subregion use the same channel, and the interference in the same subregion is managed by IA. Meanwhile, adjacent subregions use non-overlapped channels to separate neighbor IA units. Fig. 3 is an illustration of the proposed network planning.

We assume that there are N APs deployed uniformly in the WLAN, and the coverage radius of each AP is r. The set of non-overlapped channels is denoted as $\mathbf{C}$, and N is far larger than the number of non-overlapped channels.

To implement the proposed network planning and increase the DoF as much as possible, the size of each subregion should be determined first, and the appropriate working channel for each subregion should be allocated to suppress inter-subregion interference. In particular, if each subregion only contains one BSS, the proposed network planning is simplified to the traditional network planning.

In order to simplify the analysis, we assume that each subregion has the same number of BSSs (but a specific subregion may have a different number of BSSs if the number of BSSs is not an exact multiple of the subregions number), and the "cell" of each BSS is a hexagon.

Let the interference range of each AP be d. And the number of BSSs in each subregion is denoted as k. The maximum number of BSSs in each subregion k_{max} is related by d and r.

In order to realize IA, all BSSs in the same subregion must be in the same interference channel. That is, the maximum distance between BSSs (i.e., the maximum distance between any two nodes in these BSSs) in the same subregion can not be larger than the interference range. Therefore, the area of the subregion must be no more than that of a circle with the radius of $d/2$.

The area of a hexagonal BSS is

$$S = 6 \times \frac{\sqrt{3}r}{2} \times \frac{r}{2}, \tag{1}$$

and an loose constraint is

$$k \times S \leq \pi \times (\frac{d}{2})^2. \tag{2}$$

Therefore,

$$k \leq \frac{\pi d^2}{6\sqrt{3}r^2}. \tag{3}$$

The whole network will be divided into L subregions, where $L = \lceil N/k \rceil$. And it is a k-user IA model in each single subregion. In particular, if N/k is not an integer, a specific subregion will have a different number of BSSs whereas other subregions contain k BSSs, and it is a k'-user IA model ($k' < k$) in this specific subregion.

After the subregion partition, the appropriate channel should be allocated for each subregion. The channel used by the i-th subregion $C(S_i)$ should obey

$$C(S_i) \in \boldsymbol{C}, \quad i = 1, 2, \ldots, L. \tag{4}$$

According to (3) and (4), a number of possible subregion partition schemes with different subregion size could be obtained, and plenty of feasible channel allocation schemes for each subregion partition will be generated.

Since the area boundaries of subregions are irregular, (3) may get a value of k which does not accord with the distance constraint of the IA implementation (i.e., two BSSs in the same subregion is out of the interference range of each other and IA can not be implemented). An additional process for checking the validity of each subregion partition should be implemented before the DoF calculation.

In each possible subregion partition and channel allocation scheme, the specific average DoF of the whole network can be obtained. Then the appropriate scheme with the maximum average DoF could be chosen.

In the next section, the method of calculating the DoF in a given subregion partition and channel allocation scheme will be illustrated in details.

IV. THE DOF CALCULATION IN THE PROPOSED NETWORK PLANNING MANNER

A. THE AVERAGE DOF OF TWO SUBREGIONS

Let $d(S_i, S_j)$ denote the minimum distance between a BSS in subregion i and that in subregion j. And the average DoF of subregion i and j are denoted as f_i and f_j, respectively.

Case 1: $d(S_i, S_j) > d$ or $C(S_i) \neq C(S_j)$.

In this case, the distance between two subregions is larger than the interference range, or two subregions are working on different channels. Therefore, these two subregions do not interfere with each other.

Assume that there are n_i and n_j BSSs in subregion i and subregion j, respectively. The overall DoF of subregion i is $f_i \times n_i$, and that of subregion j is $f_j \times n_j$.

Then, the average DoF of these two subregions is the weighted average value of each subregion.

$$f(i,j) = \frac{f_i \times n_i + f_j \times n_j}{n_i + n_j}. \tag{5}$$

Case 2: $d(S_i, S_j) \leq d$ and $C(S_i) = C(S_j)$.

In this case, subregion i interferes with subregion j. Only one subregion can transmit at the same time because of interference.

The transmission opportunity of each BSS should be the same when taking the fairness into account. With the average DoF of f_i, on average, each BSS in subregion i can transmit f_i messages in a time unit, and it will take $1/f_i$ time units to make each BSS in this subregion transmit one message. Similarly, it will take $1/f_j$ time units to make each BSS in subregion j transmit one message. Therefore, each BSS transmit one message will spend $1/f_i + 1/f_j$ time units.

Thus, the average DoF in this case can be calculated by

$$f(i,j) = \frac{1}{\frac{1}{f_i} + \frac{1}{f_j}}. \tag{6}$$

It should be noted that the DoF calculation in (5) and (6) is independent of whether IA is used or not. For example, if the size of a subregion is 1, no IA is needed in this subregion, the average DoF of two subregions can also be calculated by (5) or (6) according to the distance between subregions and the channels they use.

The average DoF can be calculated by (5) and (6) if there are only two subregions. Nevertheless, in a real network, there are probably more than two subregions. In the network with a large quantity of subregions, the interference relationship will be more complicated.

B. DOF CALCULATION THROUGH INTERFERENCE GRAPH

In most scenarios with a number of subregions, the interference relationships among subregions are complicated. For example, in the scenario with 5 subregions shown in Fig. 3, subregion 1 interferes with subregion 5 while $d = 4r$, and subregion 3 interferes with subregion 4. The rest subregions do not interfere with each other. In this case, 3 subregions can transmit messages at the same time.

In this section, the connected graph (interference graph) is introduced to calculate the average DoF.

The interference graph $G(V,E)$ can be generated according to the interference relationships among subregions. V is the vertices set which denotes the set of subregions. And E is the edges set which denotes the set of interference relationships among subregions. If vertex (subregion) v_i and vertex v_j interfere with each other, an edge $e(v_i, v_j)$ will exist in the graph G.

Let's take the subregion partition and channel allocation scheme shown in Fig. 3 as an example. There are 5 subregions in the network, therefore, the graph has 5 vertices, and the interference graph is shown as Fig. 4.

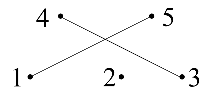

FIGURE 4. An illustration of the interference graph.

FIGURE 5. An illustration of the new graph G'.

If there is no edge in graph G, all subregions can transmit at the same time, and the average DoF is the weighted average value of each subregion. Conversely, if graph G is a complete graph in which every pair of vertices are connected by a unique edge, only one subregion can transmit at a certain moment.

In most cases, graph G has edges but it is not a complete graph. In these common situations, the average DoF can not be calculated directly. And the graph should be divided into several connected components. After the average DoF of each connected component is obtained, the average DoF of the whole network can be calculated. Therefore, the calculation of the average DoF in a general situation should be implemented in several steps.

Step 1: Divide the graph into several connected components

In the interference graph $G(V,E)$, a connected component refers to a maximal connected subgraph in which each vertex can reach all other vertices directly or indirectly through edges. Obviously, all subregions in a connected component are working on the same channel, and each subregion interferes with all or part of other subregions.

Let's replace all connected components with vertices, then a new graph $G'(V', E')$ will be generated. The new graph is illustrated as Fig. 5. Vertex 1 in graph G' means a connected component (i.e., vertex 1, vertex 5 and the edge between them in Fig. 4) in graph G, and vertex 3 indicates the other connected component.

Obviously, there is no edge in the new graph G', and the vertices (i.e., connected components in the original graph) do not interfere with each other. Similar to (5), the average DoF of the whole network can be calculated by

$$f = \frac{\sum_{i=1}^{N_{G'}} \left\{ f_{iG'} \times n_{iG'} \right\}}{\sum_{i=1}^{N_{G'}} n_{iG'}}, \tag{7}$$

where $N_{G'}$ is the number of vertices in graph G', $f_{iG'}$ and $n_{iG'}$ is the average DoF and the BSSs number of the i-th vertex in graph G' (i.e., the i-th connected component in graph G), respectively.

Therefore, in order to calculate the average DoF, all connected components should be found. Connected components

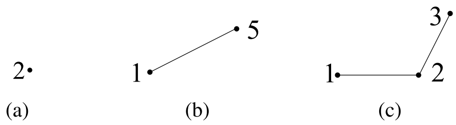

FIGURE 6. Three different cases for connected component G_i. (a) Case 1. (b) Case 2. (c) Case 3.

can be obtained by the connectivity matrix

$$A(G') = (a_{ij})_{N_{G'} \times N_{G'}}, \tag{8}$$

where

$$a_{ij} = \begin{cases} 1 & (v_i, v_j \in V',\ (v_i, v_j) \in E') \\ 0 & (v_i, v_j \in V',\ (v_i, v_j) \notin E') \end{cases} \tag{9}$$

In the connectivity matrix, all connectivity components can be obtained through Depth-First-Search or Breadth-First-Search [22].

According to (7), the average DoF of the whole network can be calculated after the average DoF of each connected component is calculated.

Step 2: Calculate the average DoF of connectivity components

Let's denote the i-th connectivity component as $G_i(V_i, E_i)$ which is also a connected graph. There are three different cases for connectivity component G_i, as shown in Fig. 6.

Case 1: Connectivity component G_i has only one vertex.

In this case, the average DoF of G_i can be obtained directly.

Case 2: Connectivity component G_i is a fully connected graph.

If graph G_i is a fully connected graph, as shown in Fig. 6(b), all subregions in this graph interfere with each other, and they need to access the channel in turn. Similar to (6), the average DoF of G_i in this situation can be calculated by

$$f_{iG'} = \frac{1}{\sum_{j=1}^{N_{G_i}} \frac{1}{f_{jG_i}}}, \tag{10}$$

where N_{G_i} is the number of vertices in graph G_i, and f_{jG_i} is the average DoF of subregions which are denoted by the j-th vertex in graph G_i.

Case 3: Connectivity component G_i is not a fully connected graph.

If this graph is not a fully connected graph, some subregions without interference can transmit at the same time. Fig. 6(c) shows a graph in this type. It should be noted that all connected components in Fig. 4 do not satisfy this condition, and Fig. 6(c) is just an illustration of this type of graphs.

In Fig. 6(c), vertex 1 and vertex 3 can transmit messages at the same time, but vertex 2 can not transmit messages while vertex 1 or vertex 3 is transmitting. Therefore, we need to find the vertices which can transmit messages at the same time (i.e., vertices without edges in connectivity component G_i).

In order to find these vertices, the complement of graph G_i is introduced. The complement $\overline{G}_i(V_i, \overline{E}_i)$ is a new graph,

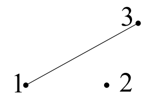

FIGURE 7. The complementary graph $\overline{G}_i$.

where $\overline{E}_i$ is the complementary set of E_i. The complementary graph $\overline{G}_i$ for Fig. 6(c) is shown as Fig. 7.

In the complementary graph $\overline{G}_i$, a maximal clique (maximal fully connected subgraph) means that vertices in this clique can transmit at the same time. And different cliques can not transmit at the same time due to interference.

Thus, if all maximal cliques are found and replaced with new vertices to generate a new graph $\overline{G}_i'$, the vertices in $\overline{G}_i'$ can't transmit at the same time, and the average DoF in this case is

$$f_{iG'} = \frac{1}{\sum_{j=1}^{N_{\overline{G}_i'}} \frac{1}{f_{j\overline{G}_i'}}}, \tag{11}$$

where $N_{\overline{G}_i'}$ is the number of vertices in the new graph $\overline{G}_i'$, and $f_{j\overline{G}_i'}$ is the average DoF of subregions which are denoted by the j-th vertex in the new graph $\overline{G}_i'$ (i.e., the j-th maximal clique or normal vertex in graph $\overline{G}_i$).

If a vertex in $\overline{G}_i'$ refers to a maximal clique in $\overline{G}_i$, the calculation of the average DoF requires an additional step to find the maximal clique. Otherwise, If this vertex in $\overline{G}_i'$ indicates a normal vertex in $\overline{G}_i$, the average DoF of the vertex can be obtained directly.

Step 3: Find maximal cliques if necessary and calculate the average DoF of each maximal clique

The Born-Kerbosch algorithm is a classic algorithm for maximal cliques. And some improved algorithms with new architectures [23] are proposed. In this paper, the complexity of the maximal clique problem is not considered because the DoF calculation just need be executed once.

Assume all maximal cliques are found, and the j-th clique is denoted as G_j^C. The DoF of this clique can be calculated by

$$f_{j\overline{G}_j'} = \frac{\sum_{k=1}^{N_v^{G_j^C}} \left\{ f_k^{G_j^C} \times n_k^{G_j^C} \right\}}{\sum_{k=1}^{N_v^{G_j^C}} n_k^{G_j^C}}, \tag{12}$$

where $N_v^{G_j^C}$ is the number of vertices in clique j, $f_k^{G_j^C}$ and $n_k^{G_j^C}$ is the average DoF and the BSSs number of the k-th vertex in graph G_j^C, respectively.

In summary, the average DoF of the whole network can be calculated through (7)(10)(11)(12). And the flowchart for the DoF calculation is shown as Fig. 8.

C. THE DOF IN A SUBREGION

The BSSs in the same subregion work on the same channel, and they are in the interference range of each other.

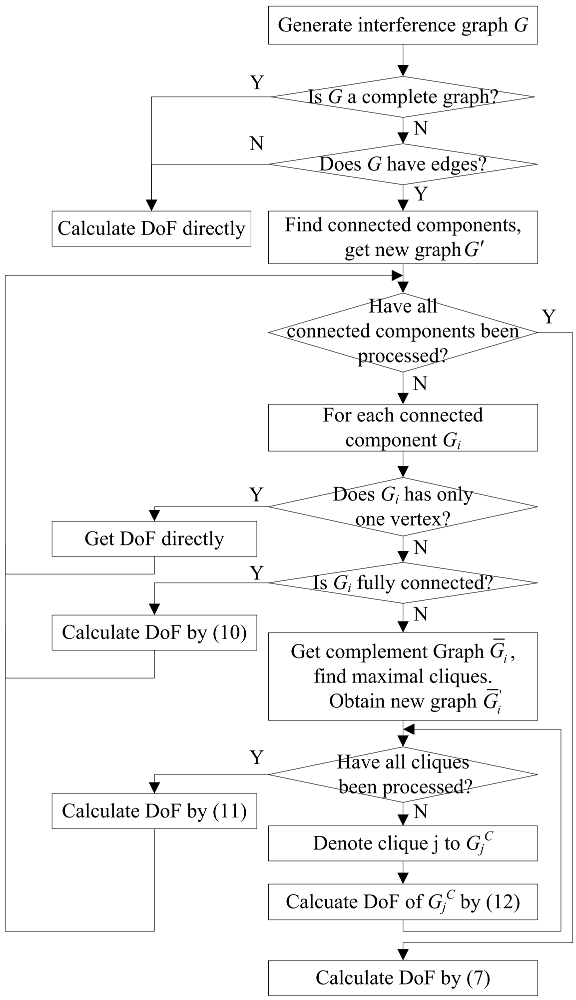

FIGURE 8. The flowchart for the DoF calculation.

Thus, the whole subregion can be regarded as an interference channel. In the WLAN scenarios, CSIT can not be obtained by commercial WLAN devices. Recall that BIA can obtain DoF gains without CSIT, and the reconfigurable antenna which is supported by the latest IEEE 802.11 standard is an implementation manner of BIA. Therefore, reconfigurable-antenna-based BIA is a realizable implementation of IA in WLANs.

In the situation where each STA has M antennas and each AP has a reconfigurable antenna [18], the DoF of k-BSS subregion (k-user BIA) is

$$DoF = \frac{kM}{k+M-1}, \tag{13}$$

where k is the number of BSSs in the subregion, and M is the number of antennas for STAs. Therefore, the average DoF of each BSS is

$$DoF = \frac{M}{k+M-1}. \tag{14}$$

It is easy to see that the average DoF is less than 1. In a sparse network, it is not an attractive value. However, in a high density WLAN, co-channel interference exists and it is probably very serious. In the traditional network planning manner, the average DoF of the whole network decreases significantly (e.g., the average DoF in Fig. 2 is 1/3). On the other hand, co-channel interference can be controlled by IA in the proposed manner, and it will potentially obtain a higher average DoF value.

According to the average DoF of each subregion and the DoF calculation illustrated in Section IV-B, the average DoF in each candidate subregion partition and channel allocation scheme can be obtained. Then, the most appropriate scheme with the largest average DoF will be selected.

When selecting the appropriate subregion size, the complexity of IA should be considered. With the increase in the value of k, the number of antenna mode switching will increase too. Since mode switching of the reconfigurable antenna incurs time delay and energy consumption, the complexity of reconfigurable-antenna-based IA is mainly reflected in switching delay and energy consumption. With the complexity of IA considered, a smaller subregion should be chosen in the case the average DoF in two different subregion partition schemes is almost the same. But a certain increase in complexity is acceptable if the average DoF is improved significantly.

V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed network planning manner, this paper simulates the average DoF in the proposed network planning manner and the traditional manner.

Three different scales of WLANs are considered in the simulations. The first one is a relatively small scale network with 27 APs (i.e., the scenario shown in Fig. 3). The second one is a middle scale WLAN with 60 APs. And the last one is a large scale WLAN with 100 APs.

In all simulation scenarios, APs are deployed uniformly, and the interference range is 30 meters. In each BSS, 10 STAs are associated with the AP, and each STA has 2 antennas while the AP has a reconfigurable antenna. Non-overlapped channels used in the simulations are Channel 1, Channel 6 and Channel 11 in 2.4GHz WLAN.

For each network planning manner with a certain subregion partition and channel allocation scheme, the average DoF is obtained, then the best average DoF and the corresponding subregion size is chosen.

The density of AP deployment affects the network performance, thus, simulations are carried out in difference deployment density. 3 typical distances (i.e., 6 meters, 10 meters and 15 meters) between neighbor APs are considered.

A. THE NETWORK WITH 27 APS

An illustration of this scale of network is shown as Fig. 3. The simulation results are shown in Fig. 9. The number of BSSs in each subregion is 1 indicates that no IA is used, and it is the same as the traditional manner. As analyzed in Section III, the average DoF without IA is 1/3 when the AP distance

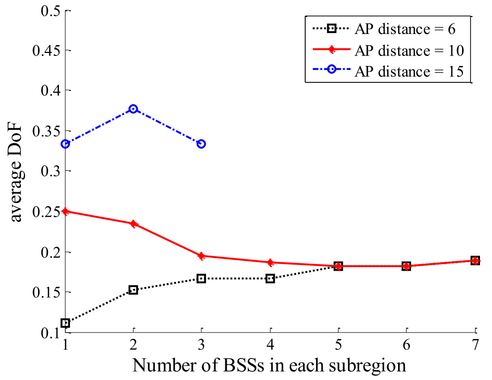

FIGURE 9. Simulation results in scenarios with 27 APs.

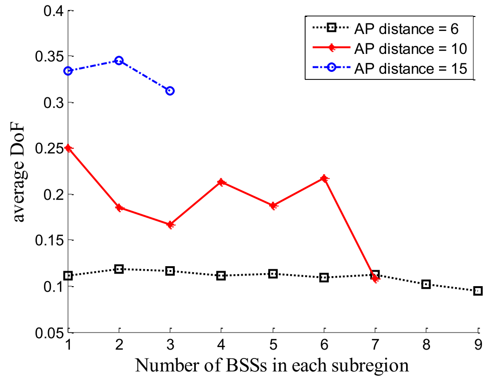

FIGURE 11. Simulation results in scenarios with 60 APs.

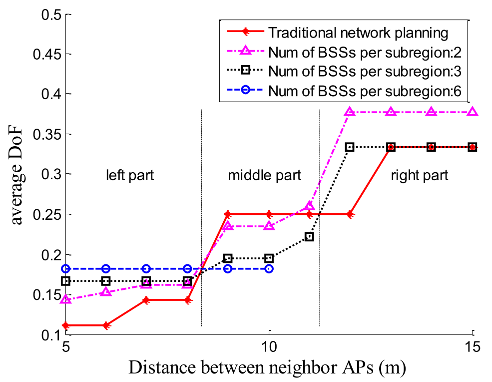

FIGURE 10. Average DoF with different density in scenarios with 27 APs.

(i.e., the distance between neighbor APs) is 15 meters. While the AP distance is less than 15 meters, co-channel interference become serious, and the average DoF decreases significantly.

When the distance between neighbor APs is 15 meters, the interference range is 2 times of the distance between neighbor APs. In this case, at most 3 BSSs can be in the same subregion because BSSs in the same IA unit must be in the interference range of each other.

It is seen that the proposed network planning manner can achieve better average DoF than the traditional manner by using the appropriate subregion size (e.g., the number of BSSs in each subregion is 2) when the distance between neighbor APs is 15 meters or 6 meters.

However, when the distance between neighbor APs is 10 meters, the proposed network planning manner get a lower average DoF than the traditional manner.

When the network is very dense, a large subregion can separate interference channels well, and it can achieve a relatively higher average DoF value. On the other hand, in the low density scenarios, IA with the small subregion size can improve the average DoF. But when the AP deployment is middle dense (e.g., the interference range is 3 times of the distance between neighbor APs), although IA can get a certain DoF gain in the subregion, the interference among subregions remain exists, and the average DoF is even lower than the traditional manner.

Fig. 10 shows the average DoF with difference density. 4 typical values of subregion size (i.e., 1 which indicates the traditional manner, 2, 3 and 6) are considered. Generally, the scenarios with larger distances between neighbor APs obtain better performance.

The right part of Fig. 10 indicates relatively low density WLANs. In these cases, the proposed scheme is slightly better than the traditional manner when the appropriate subregion size is used. The middle part of Fig. 10 indicates middle density scenarios. Although the proposed scheme can control the intra-subregion interference, inter-subregion interference still exists. And the performance in the proposed manner is even worse than that in the traditional manner. On the other hand, in high density WLANs (i.e., the left part of Fig. 10), interference is very serious, although the performance in the proposed manner is worse than the middle part, the proposed manner can achieve a significant gain than the traditional manner since the intra-subregion interference can be controlled by IA and the inter-subregion interference can be suppressed through channel allocation.

The complexity of IA will increase with the increase of k (i.e., the number of BSSs in each subregion). In the right part of Fig. 10, the subregion size $k = 2$ obtains the largest average DoF, and the corresponding complexity of IA is also the lowest (except the traditional manner). Therefore, in the right part, the subregion size of 2 should be selected. On the contrary, in the left part of Fig. 10, the subregion size $k = 2$ obtains a smaller average DoF value than other subregion size. And it is a trade-off between the complexity of IA (e.g., switching delay and energy consumption) and the network throughput when determining the size of the subregion. For example, when the distance between neighbor APs is 8, the average DoF in different subregion size is very close, and the complexity of IA should be considered while selecting the most appropriate subregion size.

B. THE WLANS WITH 60 APS AND 100 APS

To evaluate the performance in larger scale WLANs, we simulate the proposed network planning manner in scenarios with 60 APs and 100 APs.

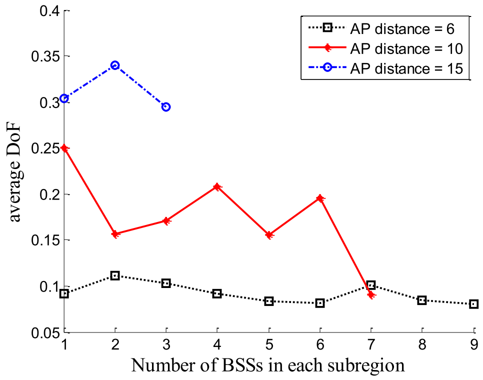

FIGURE 12. Simulation results in scenarios with 100 APs.

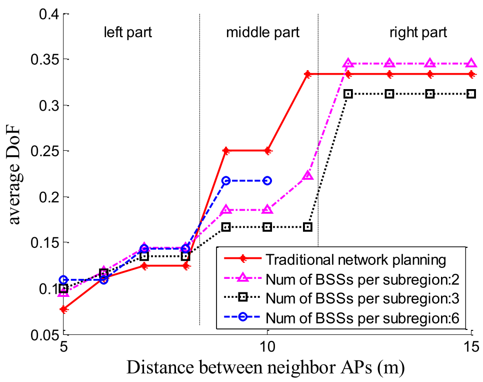

FIGURE 13. Average DoF with different density in 60 APs scenarios.

The simulation results are shown as Fig. 11 and Fig. 12. In order to implement IA, all BSSs (including all nodes in these BSSs) in a single subregion must be in the interference range of each other. In the case the distance between neighbor APs is 15 meters, at most 3 BSSs are allowed in the same subregion. And there are at most 7 BSSs in a single subregion if the distance between neighbor APs is 10 meters.

Compared with the scenarios with 27 APs, the average DoF is much lower, and that in the scenarios with 100 APs is the lowest. Because the interference among co-channel BSSs will spread and interact when the scale of the network increases. In a small scale network, a large proportion of subregions are edge subregions which have no interference in some directions. But in a large scale network, a part of edge subregions turn into central subregions, and the interference become more serious.

Fig. 13 and Fig. 14 show the average DoF with difference density in the scenarios with 60 APs and 100 APs, respectively.

In high density scenarios (i.e., the left part in Fig. 13 and Fig. 14), the proposed manner can achieve better DoF than the traditional manner in most cases. And in relatively low density scenarios (i.e., the right part in Fig. 13 and Fig. 14), the proposed manner is better than the traditional manner with the appropriate subregion size (i.e., 2 BSSs in each subregion). But in middle density scenarios (i.e., the middle

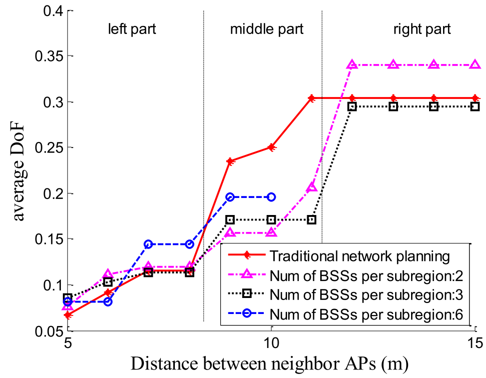

FIGURE 14. Average DoF with different density in 100 APs scenarios.

part in Fig. 13 and Fig. 14), the traditional manner obtains higher average DoF.

The precondition of improving the average DoF by IA is that IA subregions should be separated by the channel allocation. The subregion is larger than a single BSS, thus the channel allocation for subregions can separate co-channel interference more easily than the traditional manner. But in the case the subregions can not be separated by channel allocation, the performance will be probably worse than the traditional manner because the average DoF in each subregion is lower than that without IA.

In the right part of Fig. 13 and Fig. 14, the subregion size $k = 2$ which has the lowest complexity obtains the largest average DoF. Obviously, this subregion size should be selected. In some cases, the average DoF in different subregion size is very close (e.g., the left part in Fig. 13), the smallest subregion size (i.e., $k = 2$) should be selected while taking the complexity of IA into account.

VI. CONCLUSION

This paper proposed a network planning manner in density WLANs. In the proposed manner, the whole network is divided into some subregions. BSSs in the same subregion use the same channel and constitute an interference channel, and the intra-subregion interference is managed by IA. On the other hand, the inter-subregion interference is controlled by the channel allocation. To utilize the proposed network planning manner to improve the network throughput, the most appropriate subregion size and channel allocation scheme should be chosen. We use the average DoF to select the appropriate subregion size and channel allocation scheme. Then, the interference graph and the maximal clique is utilized to calculate the average DoF. To evaluate the proposed scheme, we simulated the scheme in scenarios with different network scales and difference AP deployment density, the results show that the proposed scheme improves the average DoF by using appropriate subregion size.

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