Optimal frequency assignment for IEEE 802.11 wireless networks

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Summary

The performance of wireless local area networks (WLANs) is based on the performance of the corresponding access points (APs). Nowadays, network engineers tend to manually assign data channels (frequencies) for each AP. They only use channels 1, 6, and 11 because no interference exists between these channels. But it will be far more efficient if all 11 channels are used. Therefore, the channel allocation problem becomes a major challenge when deploying WLANs. In this paper, we assume that the location of each AP is known. Our objective is to optimally assign a frequency for each AP such that the throughput is maximized and the interference between the various APs is minimized. We also consider a realistic scenario where the APs are not in line of sight of each other, but on the other hand there are different barriers that separate them. We formulate the problem using integer linear programming (ILP) in order to obtain the optimal frequency assignment (OFA). Then, we propose two efficient heuristic algorithms to achieve the same results. Finally, we evaluate the performance of all techniques and make a comparison between them. Copyright © 2008 John Wiley & Sons, Ltd.

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1.   Introduction

In an enterprise environment with many users, supporting data between users over a wide area is likely to be of the wireless multi-hop nature. Architectural reasons as well as inherent limitations of current protocol stack design are primary issues relating to scaling aggregate end-to-end throughput in wireless networks. Typically, channel assignment problem and methods for managing and controlling the distributed network are important issues in multi-hop wireless networks research. It is well known that the communication between neighboring nodes in IEEE 802.11-based network occurs *via* a contention-based mechanism which is governed by the base 802.11 multiple access (MAC) protocol, the distributed coordination function (DCF), or CSMA/CA. Accordingly, the key to one-hop capacity scaling is enhancing spatial reuse which is directly proportional to the number of orthogonal channels available in narrowband systems such as FDMA. There is only a very limited number of such orthogonal channels: 3 in 802.11b in the 2.4 GHz band and between 9 and 12 in 802.11a in the 5 GHz band depending on available bandwidth and channelization [1].

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A particular issue that is of interest to us here is the channel assignment problem due to the fact that although multiple channels are available, usually only small number of these channels are utilized due to certain constraints.

In particular, in this paper our objective is to mathematically formulate the channel assignment problem using ILP and produce the optimal solution that leads to an improved end-to-end throughput and a minimized channel interference. In addition to the main objective, we develop two efficient heuristic algorithms that achieve similar results and then compare them with the optimal solution.

Increasing network capacity and utilization by exploiting the use of multiple channels and channel reuse opportunities has been extensively researched in literature over the years. In the early work presented in References [2,3], for example, different approaches including a distributed dynamic channel assignment algorithm that is suitable for shared channel multi-hop networks and joint routing and scheduling to satisfy end-to-end demand were proposed. In References [4–6], the idea of using an arbitrary graph modeling approach was introduced which lead the researchers to show that many scheduling problems are NP-hard. Furthermore, it is important to note here the issue of scalability in wireless network which was discussed in the work of Gupta and Kumar [7]. In particular, they have investigated the asymptotic capacity problem of a multi-hop *fixed* wireless network. They showed that such network scales as $\Theta(W\sqrt{n})$ bit-meters per second for arbitrary network, and for random network, the network capacity scales as $\Theta\left(W\sqrt{(n/\log n)}\right)$ bits per second. Here, each node is capable of transmitting W bits per second, and n is the number of identical nodes.

In Reference [8], the authors designed an optimal access point (AP) selection and traffic allocation algorithm for IEEE 802.11 networks. They consider coverage and capacity to be two key issues when selecting APs in a demand area. The optimization they used balances the load on the entire network whereby demand clusters will not necessarily select the closest AP that has the largest signal level but one that can still service the demand cluster and provide ample bandwidth. As a result, APs in wireless LANs will have well-distributed traffic loads, which maximizes the throughput of the network.

In Reference [9], the authors propose an approach of optimizing AP placement and channel assignment in wireless local area networks (WLANs) by formulating an optimal integer linear programming (ILP) problem.

The optimization objective is to minimize the maximum of channel utilization, which qualitatively represents congestion at the hot spot in WLAN service areas. In Reference [10], the authors reported experimental and analytical results to address the problem of designing high-capacity WLANs based on 802.11b technology. The authors studied the impact of hidden and exposed terminal on the capacity increase in a layout of APs in a WLAN. The hidden terminal problem occurs when two or more stations outside the hearing range of each other transmit to one station that is within the hearing range of both, causing a collision [11].

Some researchers characterized the problem of assigning channels to APs as a graph-coloring problem [12]. The nodes represent APs whose channels are to be assigned. The edges represent coverage overlaps between APs, and the weights associated with the edges represent the amount of overlap measured in square meters. One would like to color the nodes (representing APs) of a graph in a way that minimizes the sum of the weights of the edges (representing coverage overlaps) connecting nodes of the same color (representing channel). This is equivalent to assigning channels to APs in a way that minimizes the total co-channel coverage overlap. Converting the channel assignment problem to a graph-coloring problem allows the known techniques used in graph coloring to be employed directly to solve the problem of channel assignment [13,14].

Our work is different in many aspects than the work presented above. The ILP formulation we designed is based on a very realistic scenario where the APs are not placed in line of sight of each other. Our formulation follows the approach presented in Reference [15] in which the authors proposed techniques to obtain optimal frequency assignment (OFA) in cellular networks. Following the ILP formulation, we present two efficient heuristic algorithms based on the minimum spanning tree (MST) problem which is a well-studied problem in graph theory. The objectives of our proposed approaches are to minimize the overall co-channel overlap and to maximize the end-to-end throughput. We next present the ILP formulation followed by the heuristic algorithms.

This paper is organized as follows. Section 2 discusses the ILP formulation of the channel assignment problem. Section 3 presents the heuristic algorithm we designed. Section 4 presents the performance of the heuristic algorithm compared to the optimal solution and Section 5 concludes the paper and presents future work.

2. ILP Formulation

In a normal wireless network, the APs are configured manually by network engineers. Typically, the frequencies (channels) are assigned for each AP in such away that the APs will not overlap (interfere) with each other. The main objective is to optimize the end-to-end throughput for the wireless network. However, if some APs are added to the wireless network, the frequency of some already existing APs has to be changed due to interference constrains. Therefore, it becomes very impractical to manually adapt the network to new change. For this reason, we develop a dynamically adaptive method that assigns a frequency for each AP such that the network throughput is maximized and the interference (overlap) between APs is minimized. To solve our problem, we mathematically formulate it using ILP.

The suggested optimal formulation is based on linear programming (LP) which is an important field in operations research that deals with solving optimization problems of a particular form. LP problems consist of a linear cost function (consisting of a certain number of variables) which is to be minimized or maximized subject to a certain number of constraints. The constraints are linear inequalities of the variables used in the cost function (also called the objective function).

If the unknown variables in the LP problem are all integers, the problem is called an '*integer programming (IP)*' or '*ILP*' problem. If only a subset of the variables are integers, the problem is called a '*mixed integer programming problem*.' If all the variables are restricted to 0 or 1, the problem is called '*binary integer programming*' problem [16]. In contrast to LP, which can be solved efficiently in the worst case, IP problems are in the worst case undecidable, and in many practical situations NP-hard.

Typically, wireless networks segment the wireless spectrum into channels, which devices use to communicate back and forth. In North America, the 2.4 GHz spectrum which supports the most popular protocols 802.11b and 802.11g, is segmented into 11 channels (Figure 1). Table I lists these channels.

When devices send traffic on the same channel, they have the potential to interfere with one another, a type of interference known as co-channel interference. Unfortunately, the problem does not end there. Each of these channels has substantial bandwidth, and therefore they have significant spectral overlap with each other. This means that the signal from a device on channel 1 could bleed over and interfere with a device on channel 2 or 3 [17,18]. As a result, there are
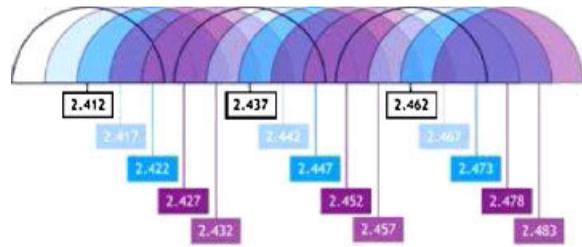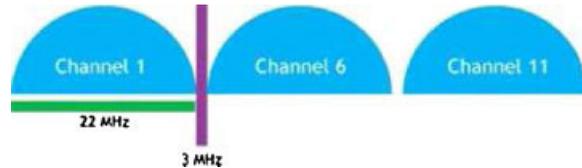

Fig.1. Adjacent overlapping channels.

Fig.2. Non-overlapping channels 1, 6, and 11.

only three non-overlapping channels in the 802.11b/g band—channels 1, 6, and 11 (Figure 2).

As it was mentioned above, the performance of a network depends, in part, on the assignment of radio channels to APs. This assignment is often done using a manual process in which the designer attempts to assign the channels in a way that minimizes co-channel overlap (interference). The coverage areas, and therefore the channel assignments, are dependent on, among other things, the radio propagation environment. But the radio propagation environment changes, so one cannot be sure that the channel assignments valid at the time the network was designed will continue to be valid [12].

We model the OFA problem using ILP, where assignment constraints, interference constraints, and an objective are defined. The frequency assignment model we use have a predefined set of channels or frequencies, denoted by F, where F is composed of 11 different channels ($F = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}$).

Table I. IEEE 802.11b/g channels in North America [17].

Channel number	Frequency (GHz)
1	2.412
2	2.417
3	2.422
4	2.427
5	2.432
6	2.437
7	2.442
8	2.447
9	2.452
10	2.457
11	2.462

An undirected graph $G(V, E)$ is a set of vertices (nodes) $V = \{v_0, v_1, v_2, \cdots, v_n\}$ that represents nodes of a network, connected together by a set of edges $E = \{e_0, e_1, e_2, \cdots, e_m\}$, where n and m are number of vertices and number of edges in the graph, respectively. Nodes in the graph connected directly by edges are called neighbors. A simple path $P_k = <v_s, v_1, v_2, \cdots, v_t>$ from a source vertex v_s to a terminal vertex v_t is a sequence of vertices starting at v_s and ending at v_t, such that every two consecutive vertices in the sequence are neighbors (having a direct edge connecting them) in the graph, and no vertex appears more than once in the sequence. If a simple path passes through a vertex more than once, a cycle is resulted. Every edge e_k in the graph represents a link connecting two hubs; the edge must have a predefined installation/usage cost $c(e_k)$. The cost function $C(P_k)$ of a given path P_k is the summation of the cost of all edges connecting vertices in the vertex sequence of the path P_k. We are assuming single edge connectivity between any two vertices, since we can always find the equivalent cost and equivalent reliability whenever parallel edges are present. Here, for every AP v, one and only one frequency $f \in F$ is assigned to v. We represent the wireless network as a graph $G = (V, E)$. Each AP is represented by a vertex $v \in V$. Two APs are connected with an edge $e \in E$ if they are within each others' range.

For each pair of frequencies $f \in F(v)$ and $g \in F(w)$, we penalize the combined choice by a measure depending on the interference level between APs v and w. This penalty is denoted by $p_{vw}(f, g)$. In our model, the penalty depends on v, w, and the distance between the frequencies $|f - g|$. Penalty $p_{vw}(f, g)$ is defined as follows:

$$p_{vw}(f, g) = \begin{cases} \frac{1 - |f - g| \times 0.2}{d_{vw}^m}, & \text{if } p_{vw}(f, g) \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

This penalty measures the interference between APs v and w, when they use channels f and g, respectively. The numerator $(1 - |f - g| \times 0.2)$ measures the relative percentage gain in interference between APs v and w as a result of using overlapping channels. The multiplier 0.2 is the overlapping channel factor which is 1/5 for 802.11b/g. d_{vw}^m represents the Euclidean distance between APs v and w, that is, $d_{vw} = \sqrt{(x_v - x_w)^2 + (y_v - y_w)^2}$, and m represents the path loss exponent. We assume $m = 2$ in our work, but m can take values of 2, 3, or 4 depending on the environment.

If APs v and w use frequencies that are five or more channels apart from each other ($|f - g| \geq 5$), then their relative penalty is zero, that is, $p_{vw}(f, g) = 0$. This is reflected in Equation (1), because if $|f - g| \geq 5$ then $|f - g| \times 0.2 \geq 1$, therefore $1 - |f - g| \times 0.2 < 0$. Equation (1) indicates that such an expression should be equal to zero. This is true because such channels ($|f - g| \geq 5$) have no co-channel overlap. Take for example channels 1 and 6, or channels 1 and 7, or channels 2 and 8, etc.; all these channels have no overlap and thus no penalty regardless of the distance between them.

But, if APs v and w use frequencies that are less than five channels apart ($|f - g| < 5$), then there exist an interference between them and they should be penalized. The penalty depends on the distance between the APs and the frequencies they use. As Equation (1) indicates, the larger the distance, the lower the penalty. The penalty is inversely proportional to the distance between the APs. If AP v uses channel 1 and AP uses channel 2, the numerator of Equation (1) indicates an 80% interference between the APs. Now, it all depends on the distance between v and w (d_{vw}). If d_{vw} is too small, the interference and thus the penalty between the APs is too large. On the other hand, if d_{vw} is too large, the penalty will be zero or close to zero and thus both APs can communicate without any problems.

The OFA problem using ILP consists of variables, constraints, and an objective. A straightforward choice for the variables is to use binary variables representing the choice of a frequency to a certain AP. For every AP v and available frequency $f \in F(v)$, we define

$$x_{vf} = \begin{cases} 1, & \text{if frequency } f \in F(v) \text{ is assigned to } AP_v \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

As discussed earlier, each AP should be assigned one and only one frequency. Equation (3) presents this constraint where AP v is assigned only one frequency $f \in F(v)$. Recall that N APs and 11 frequencies are available.

$$\sum_{f=1}^{F} x_{vf} = 1, \qquad v = 1, \cdots, N \quad (3)$$

The penalty matrices p_{vw} are often used in combination with a threshold value $p_{\max}$. Pairs of frequencies with a penalty exceeding this threshold are forbidden.
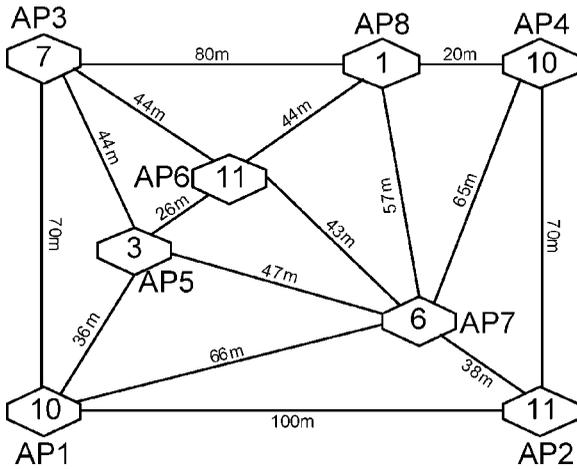
Fig. 3. Optimal frequency assignment solution using ILP.

This is modeled by the following constraints:

$$x_{vf} + x_{wg} \leq 1, \quad f \in F(v), \ g \in F(w), \ p_{vw}(f, g) > p_{\max}$$

$$(4)$$

In order to clarify Equation (4), consider two APs v and w using frequencies 1 and 4, respectively. According to the penalty matrix discussed in Equation (1), an interference (penalty) exists between the APs. Equation (4) says that if the corresponding penalty is greater than $p_{\max}$, then one of the frequencies or even both must be changed. If the penalty is less than $p_{\max}$, then the AP has appropriate frequencies and should not be changed. Sometimes it is alright to have small overlap between the APs; $p_{\max}$ allows for this to happen.

When there is no further objective to be optimized, we obtain the so-called feasibility OFA problem. Here, we simply want to find a feasible solution to the OFA problem, that is, a solution satisfying the constraints (3) and (4). Figure 3 shows the solution of the OFA problem using ILP.

In Figure 3, we considered a $100 \times 70\,\mathrm{m}^2$ building with eight APs distributed in different locations inside the building. The penalty threshold used is $p_{\max} = 0.015$. According to the result, AP 1 used channel 10, AP 2 used channel 11, AP 3 used channel 7, AP 4 used channel 10, AP 5 used channel 3, AP 6 used channel 11, AP 7 used channel 6, and AP 8 used channel 1. Those results are the optimal since the interference between the channels is the minimum and the channels of the adjacent APs have reasonable difference. Even though two APs (1 and 4) have the same channel, there is minimal interference between them since they are more than 100 m away from each other ($d \geq 100\,\mathrm{m}$).

Next, we propose the heuristic algorithms that satisfies the same objective, that is, minimize the interference while maximizing the throughput.

3. Heuristic Algorithms

Since obtaining the optimal solution using ILP works only for small numbers of APs, we propose alternative solutions to the OFA problem using two efficient heuristic algorithms. The heuristic algorithms that we propose are an extension to the well-known MST problem. As mentioned earlier, we represent the wireless network as a graph $G = (V, E)$. Each AP is represented by a vertex $v \in V$. Two APs are connected with an edge $e \in E$ if they are within each others' range. We now explain the algorithm and analyze its complexity.

3.1. Near Optimal Frequency Assignment Algorithm (NOFA)

We start by explaining what is a spanning tree and what is a MST. Given a connected, undirected graph, a spanning tree of that graph is a subgraph which is a tree and connects all the nodes together. A single graph can have many different spanning trees. We can also assign a weight to each edge, which is a number representing how unfavorable it is, and use this to assign a weight to a spanning tree by computing the sum of the weights of the edges in that spanning tree. An MST is then a spanning tree with weight less than or equal to the weight of every other spanning tree. We consider the weight on the edge to be the distance between the two nodes (APs) connecting the edge. Formally, the problem becomes: given a connected graph $G = (V, E)$ and a weight $w : E \rightarrow R+$, find an MST and while doing so assign to each node an appropriate frequency.

We use a well-known algorithm called 'Prim's Algorithm' to find the MST of a given graph. Prim's Algorithm grows the MST starting at an arbitrary node. At each stage, a new node will be added to the tree already constructed. The algorithm stops when all the nodes have been reached. The nodes of the MST spans at a rate of one node at a time during the execution of Prim's Algorithm.

We extend Prim's Algorithm by assigning a frequency to each new node added to the tree that is being constructed. We call the suggested heuristic algorithm 'NOFA.' Two variations of NOFA are presented: (1) NOFA-1 only assigns frequencies 1, 6, and 11 to the APs and (2) NOFA-2 assigns to the APs any frequency of the 11 available frequencies.

Algorithm 1: *NOFA-1*: the heuristic that only assigns frequencies 1, 6, and 11 to each AP

    Data: A connected weighted graph with vertices V and edges E

    Result: Minimal spanning tree composed of V_{new} and E_{new} where each $v \in V$ has a weight indicating its
        frequency (only frequencies 1, 6, and 11 are used)

1 **begin**

2     $V_{new} = \{x\}$, where x is an arbitrary node (starting point) from V, $E_{new} = \{\}$

3     $f_x = 1$

4   **while** $V_{new} \neq V$ **do**

5   Choose edge (u, v) from E with minimal weight such that u is in V_{new} and v is not (if there are
        multiple edges with the same weight, choose arbitrarily)

6   **if** *v has only one neighbor* **then**

7             $f_v = f_u + 5 \bmod 11$

8   **else**

9   let w be the second closest neighbor to v (u is the first neighbor)

10   choose f_v s.t. $min(|f_v - f_u|, |f_v - f_w|) = 5$

11   Add v to V_{new}, add (u, v) to E_{new}

12 **end**

Algorithm 1 describes the heuristic used to assign a specific frequency to each AP. The only frequencies used are 1, 6, and 11. We start with a set $V_{new} = \{x\}$, where x is an arbitrary initial node. We set the frequency of x to be 1. From the neighbors of x, we choose the one that is closest to x and we give it a frequency which is five channels apart from f_x; let the closest neighbor be u. Since initially $f_x = 1$, f_u should be equal 6. We add the neighbor of x to V_{new} resulting in $V_{new} = \{x, u\}$. From the neighbors of x and u, choose the one that is closest to either one of them; let this neighbor be v. If v has one neighbor, the f_v is assigned a frequency that is five channels apart from its neighbor. If v has more than one neighbor (2, 3, or more), we only take into consideration the closest two neighbors. We then assign a frequency to v that is exactly five channels apart from the frequencies of both neighbors. This is captured in lines 9 and 10 of Algorithm 1. So if the two neighbors of v has frequencies 1 and 11, then the frequency assigned to v will be $f_v = 6$. Figure 4 shows the frequency assignment when NOFA-1 is used. We use the same scenario as the one in Figure 3. Notice that APs 1 and 3 have the same frequency, but since they are far away from each other, the interference between them is minimal.

Algorithm 2 differs from Algorithm 1 in that it uses all the 11 available channels when assigning frequencies to the APs. Like Algorithm 1, we populate the tree by adding a new node to it in each loop. Each node that is added to the tree is assigned a frequency out of the 11 available frequencies. We start at any node, add it to V_{new}, and assign to it frequency 1. Then, we choose edge (u, v) from E with minimal weight such that u
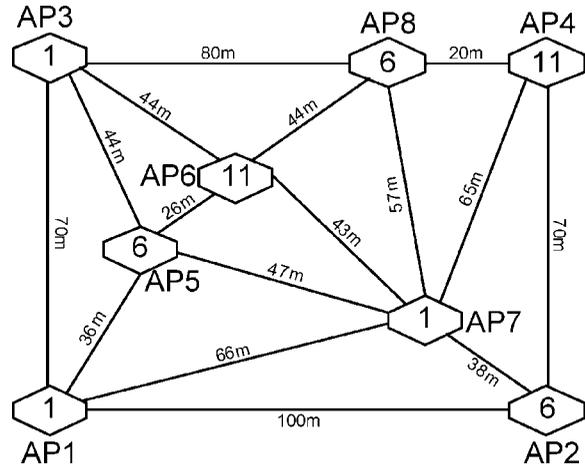

Fig. 4. Frequency assignment using NOFA-1.

is in V_{new} and v is not. If v has only one neighbor u, then assign to it a frequency that is five channels apart from u. This means that no overlap exist between the newly added node (v) and the already existing node (u). If v has two neighbors, we assign a frequency to v that is exactly five channels apart from the frequencies of both neighbors. If v has more than two neighbors (3, 4, or more), then there exist a potential to have an overlap between v and these neighbors no matter what is the frequency assigned to v. We only consider the three closest neighbors to v and assign a frequency to v that is at most five channels apart from the frequencies of all the three neighbors. This is captured in lines 12 through 17 of Algorithm 2. If we could not find a frequency for v that is five channels apart from the three

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Algorithm 2: *NOFA-2*: the heuristic that assigns appropriate frequencies to the APs

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Data: A connected weighted graph with vertices V and edges E

Result: Minimal spanning tree composed of V_{new} and E_{new} where each $v \in V$ has a weight indicating its frequency (all eleven frequencies are used)

1 **begin**

2     $V_{new} = \{x\}$, where x is an arbitrary node (starting point) from V, $E_{new} = \{\}$

3     $f_x = 1$

4   **while** $V_{new} \neq V$ **do**

5   Choose edge (u, v) from E with minimal weight such that u is in V_{new} and v is not (if there are multiple edges with the same weight, choose arbitrarily)

6   **if** *v has only one neighbor* **then**

7           $f_v = f_u + 5 \bmod 11$

8   **else if** *v has two neighbors* **then**

9   let w be the second neighbor to v (u is the first neighbor)

10   choose f_v s.t. $min(|f_v - f_u|, |f_v - f_w|) = 5$

11   **else**

12   let w and y be the second and third closest neighbors to v (u is the first neighbor)

13   choose f_v s.t. $min(|f_v - f_u|, |f_v - f_w|, |f_v - f_y|) = d$, where $d = 5$

14   **if** *f_v has multiple solutions* **then**

15   choose the channel that minimizes the penalty

16   **if** *$d = 5$ does not produce an assignment for f_v* **then**

17   try $d = 4$, then $d = 3$, then $d = 2$, then $d = 1$

18   Add v to V_{new}, add (u, v) to E_{new}

19 **end**

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closest neighbors, we search for a frequency for *v* that is four channels apart form its three closest neighbors. If still we could not find f_v that satisfies this condition, we try three channels apart, then two channels apart, then one channel apart. The furthest the channels are apart, the less the interference between APs. The algorithm stops when all nodes are visited. So if the three neighbors of *v* has frequencies 1, 6, and 11, respectively, then the frequency assigned to *v* can be 3 or 4 or 8 or 9. We choose the frequency that minimizes the penalty. For example, in Figure 5, after APs 1, 5, and 6 are assigned frequencies 1, 6, and 11, respectively, it comes the turn to assign a frequency to AP 3. NOFA-2 assigns frequency 3 to AP 3 because such assignment minimized the overlap between APs 3 and 6, APs 3 and 5, and APs 3 and 1. Figure 5 shows the frequency assignment when NOFA-2 is used. We use the same scenario as the one in Figure 3.

Fig. 5. Frequency assignment using NOFA-2.

3.2. Complexity Analysis of NOFA

Algorithm 1 is dominated by the complexity of finding the MST. We used a 'binary heap' data structure and an 'adjacency list' representation to implement Prim's Algorithm. The time complexity for finding the MST is $O((V + E)\log(V)) = O(E\log(V))$, which we con-
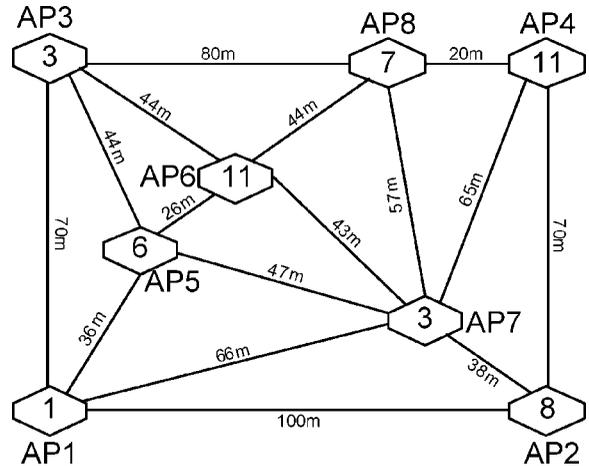
sider simple, fast, and efficient. Algorithm 2 also finds the MST, but it does some extra work in lines 6 through 17. In line 10, we try all 11 channels for *v* in order to check if any of the 11 channels satisfies the condition that says: f_v should be 5 channels apart from its two neighbors. In lines 12 through 17, the same condition is checked again. If this condition cannot be satisfied, we relax it by saying that f_v should be four channels apart from its three closest neighbors. So, we

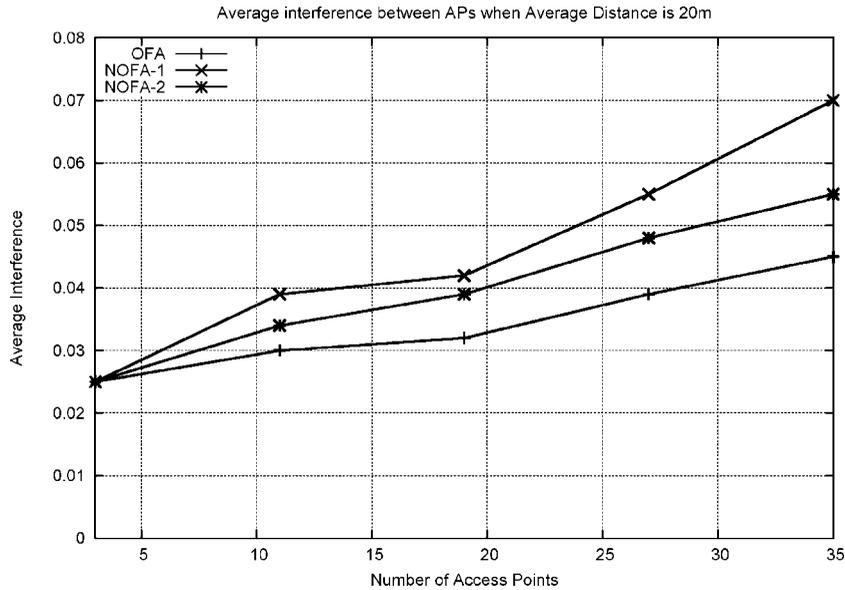Average interference between APs when Average Distance is 20m

Fig. 6. Average interference between APs when the average distance between the APs is 20 m.

make another 11 checks. In the worst case, we relax the condition four times, that is, five channels apart, then four channels apart, then three channels apart, then two channels apart, then one channel apart. A total of 11×5 trials is needed. In total 11×6 checks might be needed, but this value is considered a constant, that is, $O(1)$. Therefore, the time complexity of Algorithm 2 is also $O(E \log(V))$. Next, we present the performance evaluation of our suggested techniques.

4. Performance Evaluation

Wireless LANs of different sizes are placed in a 300×300 square area. The network size ranges from 3 APs to 35 APs. The distances between the APs is known and it is calculated using the Euclidean distance principle. Our objective is to assign a frequency to each AP such that the co-channel interference is minimized. For a given network, we apply the three methods that
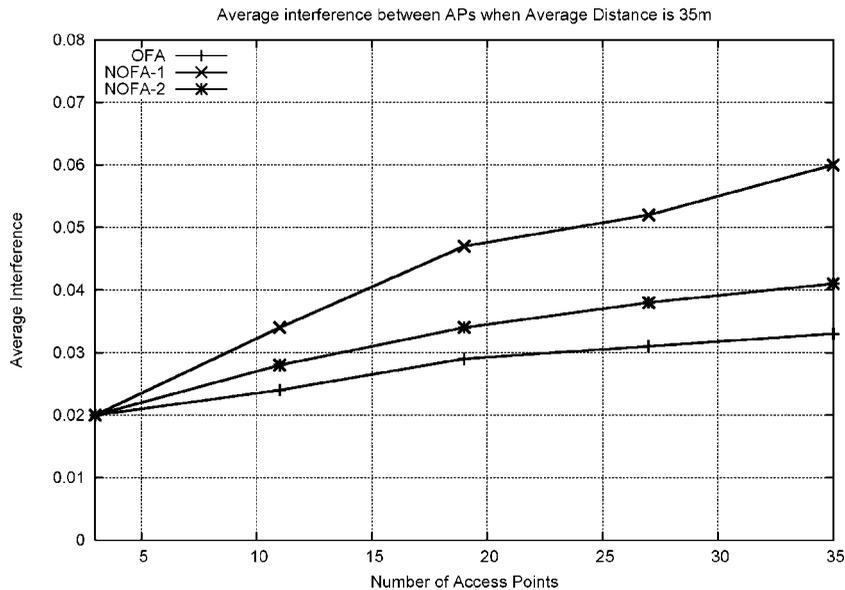
Average interference between APs when Average Distance is 35m

Fig. 7. Average interference between APs when the average distance between the APs is 35 m.

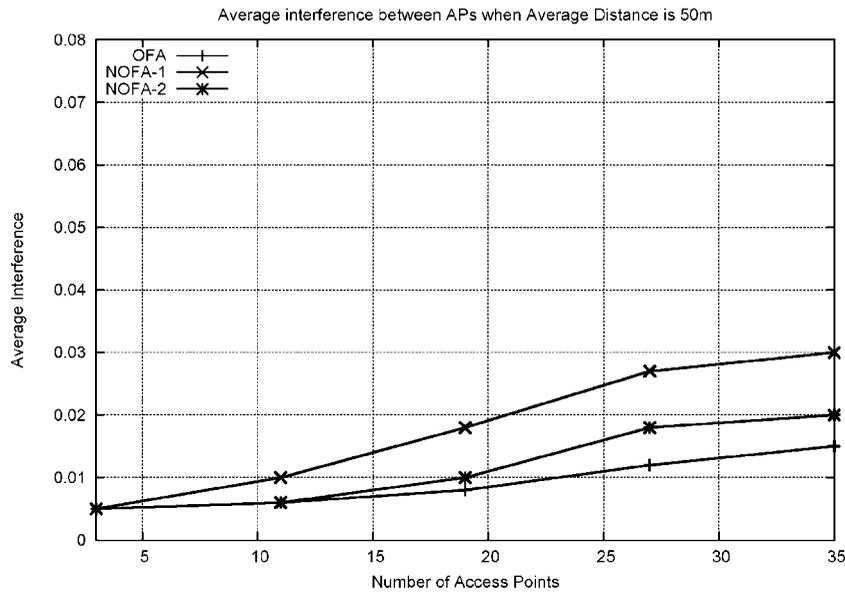Average interference between APs when Average Distance is 50m

Fig. 8. Average interference between APs when the average distance between the APs is 50 m.

we designed; OFA, NOFA-1, and NOFA-2. Each algorithm produces a certain channel assignment for the APs and each algorithm results in a certain level of interference. We execute the algorithms 20 times on networks of the same size, then we average the interference produced by each algorithm. We plot the average interference against the network size and analyze the results. We also vary the distance between the APs to check how much effect does distance have on the AP's channel assignment.

Figure 6 shows WLANs of different sizes and their corresponding average interference. In this experiment, we place the APs such that the average distance between them is around 20 m. This means that close APs with close frequencies will interfere with each other, that is, the interference caused by co-channel overlap is high. When a network of size 3 is used, all three algorithms (the optimal algorithm and the two heuristic algorithms) produce the same minimal interference. This is because, they all choose channels 1, 6, and 11 for

Average interference between APs when Average Distance is 75m
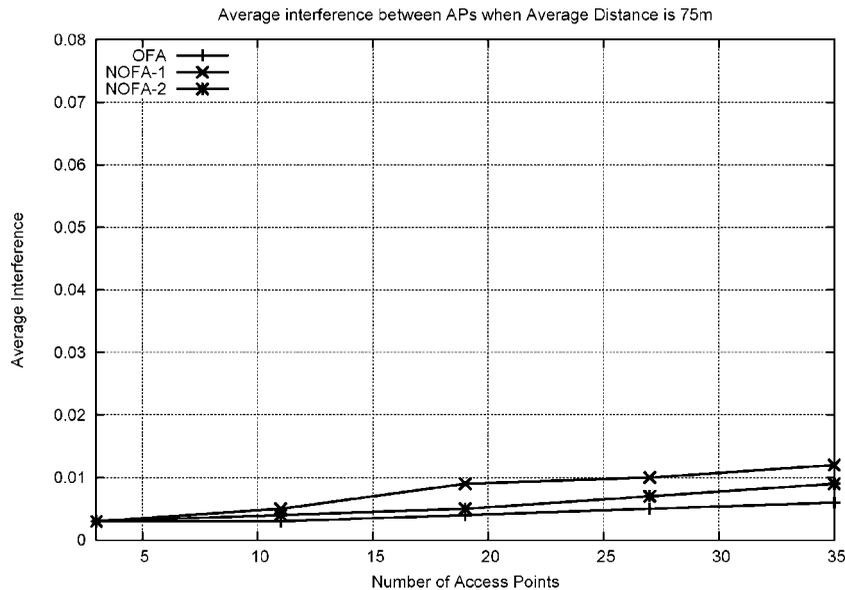
Fig. 9. Average interference between APs when the average distance between the APs is 75 m.

the three existing APs. As the network size increases, so does the interference. In such a scenario, the interference is considered a bit high because the network is condensed and the APs are in close range to each other. Even though the network is condensed, such interference is acceptable and can easily maintain a high network throughput.

Figure 7 repeats the same experiment but with higher average distance. The average distance used is 35 m. Such an average distance means that the network is still condensed and there is a big probability of having high co-channel overlap. Compared to Figure 6, the average interference level is lower, because the APs are further apart from each other.

Figure 8 increases the average distance to 50 m. The interference in such a scenario is reduced by almost 50%. This is due to the fact that even if neighboring APs use the same channel, the overlap between them will be low. In addition to this, the proposed algorithms have a crucial role in reducing the interference. The proposed algorithms are designed based on finding the MST and assigning a channel to each node visited. When the distance between nodes is large, less edges exist in the network graph. This means less node degree, which leads to a finer and more accurate choice of AP channel (NOFA-1 and NOFA-2).

In the last experiment (Figure 9), we increase the average distance to 75 m. In this scenario, all the proposed algorithms perform well. NOFA-1 and NOFA-2 produce a channel assignment that is very close to the optimal. We can conclude that the two heuristic algorithms we proposed produce a frequency assignment that is very close to optimal even when the network is condensed. When the APs are spread out, they almost give the same results as that of the optimal. NOFA-2 still works better than NOFA-1. This is because NOFA-2 uses all 11 available frequencies, while NOFA-1 uses only channels 1, 6, and 11.

5. Conclusion

In this paper, we proposed techniques to assign appropriate channels to APs such that all the 11 available channels are used. Our objectives behind such assignment are to improve the throughput and minimize the interference. We proposed three solutions to the problem. One is a mathematical formulation based on ILP. The other two are efficient heuristic algorithms based on finding the MST in a network graph. The experimental results show that the proposed heuristic algorithms

work very well and in many occasions they produce results that are very close to the optimal solution. In our future work, we plan to compare our algorithms to some methods discussed in the literature. We also plan to perform experiments on network throughput and network congestion.

References

1. Alazemi HMK, Das A, Vijaykumar R, Roy S. Fixed channel assignment algorithm for multi-radio multi-channel mesh networks. *Wireless Communications and Mobile Computing*, 2008. DOI: 10.1002/wcm.532
2. Cidon I, Sidi M. Distributed assignment algorithms for multihop packet radio networks. *IEEE Transactions on Computers* 1989; **38**(10): 1353–1361.
3. Hajek B, Sasaki G. Link scheduling in polynomial time. *IEEE Transactions on Information Theory* 1988; **34**(5): 910–917.
4. Ramaswami R, Parhi KK. Distributed scheduling of broadcasts in a radio network. *Proceedings of the 8th Annual Joint Conference of IEEE Computer and Communication Societies INFO-COM,* 1989; 497–504.
5. Ephremides A, Truong TV. Scheduling broadcasts in multihop radio networks. *IEEE Transactions on Communications* 1990; **38**: 456–461.
6. Sen A, Huson ML. A new model for scheduling packet radio networks. *Wireless Networks* 1997; **3**: 71–81.
7. Gupta P, Kumar PR. The capacity of wireless networks. *IEEE Transactions on Information Threory* 2000; **46**(2): 338–404.
8. Akl R, Park S. Optimal access point selection and traffic allocation in IEEE 802.11 networks. *Proceedings of the 9th World Multiconference on Systemics, Cybernetics and Informatics (WMSCI 2005): Communication and Network Systems, Technologies and Applications*, 2005.
9. Lee Y, Kim K, Choi Y. Optimization of AP placement and channel assignment in wireless LANS. In *27th Annual IEEE Conference on Local Computer Networks* 2002; 831–836.
10. Gordon S, Dadej A. Design of high capacity wireless lans based on 802.11b technology. In *6th International Symposium on Communications Interworking* 2002; 133–144.
11. Haidar M. Dynamic load balancing and channel allocation in indoor wireless local area networks. *PhD Thesis*, University of Arkansas, 2005.
12. Hills A, Friday B. Radio resource management in wireless lans. *IEEE Communications Magazine* 2004; **42**(12): S9–S14.
13. Brelaz D. New methods to color the vertices of a graph. *Communications ACM* 1979; **22**(4): 251–256.
14. Randall-Brown J. Chromatic scheduling and the chromatic number problems. *Management Science* 1972; **19**(4): 456–463.
15. Aardal KI, van Hoesen SPM, Koster AMCA, Mannino C, Sassano A. Models and solution techniques for frequency assignment problems. *4OR*, **1**(4).
16. Wikipedia. Linear programming 2006. http://en.wikipedia.org/wiki/Linear_programming
17. OHara B, Petrick A. *The IEEE 802.11 Handbook: A Designers Companion*. IEEE Press, Piscataway, NJ, USA, 1999.
18. IEEE 802.11. Wireless LAN medium access control (MAC) and physical layer (phy) specifications. 1997.

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