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Characterizing the Impact of Non-Uniform Deployment of APs on Network Performance under Partially Overlapped Channels

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Abstract. Partially overlapped channels were demonstrated to have the potential of improving the network performance. One example is an increased capacity in a well saturated network. We address the problem of Wi-Fi network planning incorporating partially overlapped channels by more efficiently exploring the spatial reuse to increase the network capacity. We exploit that the interference ranges for separated channels are different, which can be utilized to deploy access points non-uniformly. In this paper, we formulate the problem, show that it can not be solved in polynomial time. Therefore, we propose a greedy optimization algorithm and validate the theoretical results through computer-based simulations.

Keywords: Partially overlapped channel, Wi-Fi network, spatial reuse, channel assignment.

1 Introduction

In recent years, wireless networks have become an increasingly popular field from wireless mesh networks [1], sensor networks [2] to vehicular networks [3] to provide ubiquitous network access to users. IEEE 802.11b/g standards are among the most widely used technology for wireless networks, operating in the ISM 2.4GHz band in which 11 channels are available. The center frequencies are separated by 5 MHz, while each channel occupies a spread of about 30 MHz as shown in Fig. 1.

There are some overlapped frequencies among adjacent channels, also known as the channel interference. This channel interference decreases with the channel separation (CS) which describes the extent of the overlap. With sufficient separation (no less than 5 channels in the IEEE 802.11b standards) no interference will occur. We define channels without frequency overlap as orthogonal channels.

Currently, either one or three orthogonal channels (channel 1, 6 and 11) are employed in Wi-Fi networks. In order to improve network capacity, partially overlapped channels (POCs) were proposed. Recent work shows that a careful design of partially overlapped channels can often lead to significant improvements in spectrum utilization and network performance [5–7].

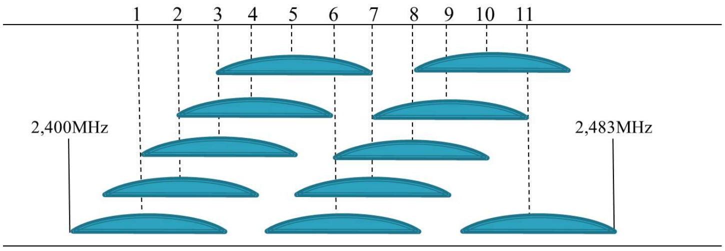


Fig. 1. Frequency spread of various channels in the IEEE 802.11b/g standard[4].

Previous work assumed a uniform[1] [8] or random [4] topology in a network. However, in practical applications, it is infeasible to deploy Access Points(APs) randomly in a WLAN based mesh network and also the placement of APs is restricted by a physical environment. We propose a new scheme combining AP appropriate deployment of APs and channel assignment to improve network capacity.

The contributions of our work are as follows:

1. We consider the practical issue of non-uniformly deploying APs in a one-dimensional topology, for instance, the access network along the subway or metro-rail platform.
2. We propose a greedy algorithm to solve the problem due to computational intractability.
3. Finally, we evaluate the uplink throughput and show via simulations that our scheme outperforms the uniform AP deployment.

The paper is organized as follows. We discuss the related work in Section 2. The problem formulation is described in Section 3. Our proposal combining AP deployment with channel assignment is presented in Section 4. Performance evaluations are given in Section 5. Conclusions and future work are given in Section 6.

2 Related Work

Previous work on POCs ranges from network analysis [5–7, 9] to concrete technologies [4, 10, 8] for the allocation of POCs to APs in practice.

The work in [5], Mishra et al. defined and modelled POCs in wireless environments. The authors measured the amount of partial overlap between two channels from the physical layer and gave the numerical result as interference vector (IV) as shown in table 1. In this paper, we also utilize IV to decide whether two channels interfere.

[1] Here, the definition of uniform deployment is that the distance between Access Points is the same, otherwise, it is non-uniform deployment

Table 1. An interference Vector conditioned on the channel separation. For instance, for a channel separation of 2 (e.g. channels 3 and 5), the minimal distance for two APs to communicate simultaneously without interfering each other should be at least 190 meters. Also, for a channel separation of 5 or above, no interference is observed even when APs share their location

Channel Separation	0	1	2	3	4	5	6	7	8	9	10
Distance [meters]	300	280	230	170	70	0	0	0	0	0	0

Mishra et al. also applied the model in the contexts of WLANs and wireless mesh networks with the result that POCs can improve throughput by factors between 1.6 and 2.7. Based on this work, in [9], Feng et al. derived an analytical formulation to calculate the improvement in network capacity compared to utilizing orthogonal channels in networks of string, grid and random topologies. More recently, channel assignment algorithms have been proposed using POCs. A POC-based channel assignment algorithm was proposed in [4] utilizing a new interference model I-Matrix to select channels with less interference. Following this concept, the authors of [10] assigned POCs in wireless mesh networks. By modelling this as a game-theoretic problem, a near-optimum solution could be obtained [8]. However, these methodologies can not be applied in practice in Wi-Fi networks due to the hardness of dynamically detecting the information of radios when a pair of nodes want to communicate with each other. Finally, the Aileron system was proposed in [11], which embeds channel control information in the modulation type so that client and AP need not be tuned to identical channels. This method is feasible to recognise calls of APs and clients.

3 Problem Formulation

In this section, we first discuss the system and interference model before we formulate the problem analytically.

3.1 System Model

With extensive use of smart phones and other wireless devices, such as PDAs and tablet computers, a Wi-Fi network can be rapidly deployed and provide the communication service to cover "the last mile". Such Wi-Fi hotspots are frequently employed in areas with high user density. APs at single channels can typically provide good communication services to about 20 users. In order to better exploit spatial reuse, APs could utilize POCs as illustrated in Fig. 2.

3.2 Interference Model

We utilize the interference model described in Section 2. We deploy APs non-uniformly since the interference ranges for different channel separations differ greatly. By exploiting this property carefully, we can improve the network capacity. For example, assume interference vector (IV) as

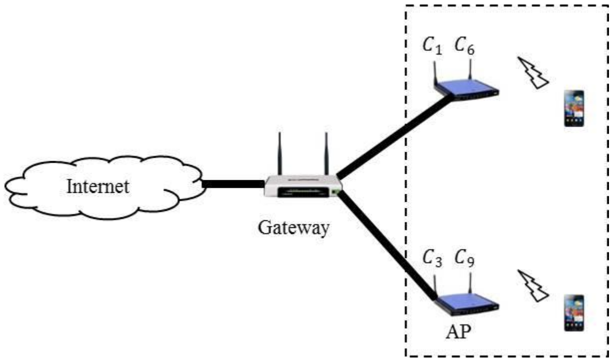


Fig. 2. Wi-Fi network infrastructure utilising POCs. The top AP is assigned channel 1 and 6 while the second is assigned channels 3 and 9.

$$[210 \ \ 190 \ \ 160 \ \ 70 \ \ 10 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0],$$

a communication range of 120 meters and the optimal uniform deployment depicted in Fig. 3(a). When APs are uniformly deployed with a distance of at least 150 meters between neighbours, there are at most 14 channels that can be simultaneously active without interfering with each other as shown in Fig. 3(a). However, with a careful non-uniform deployment, up to 15 channels can be active at a time as shown in Fig. 3(b).

In this paper, we analyze one-dimensional distribution topologies in which all APs are queued in a line. This would, for instance, occur in the access network along a subway platform.

3.3 Formulation of the Problem

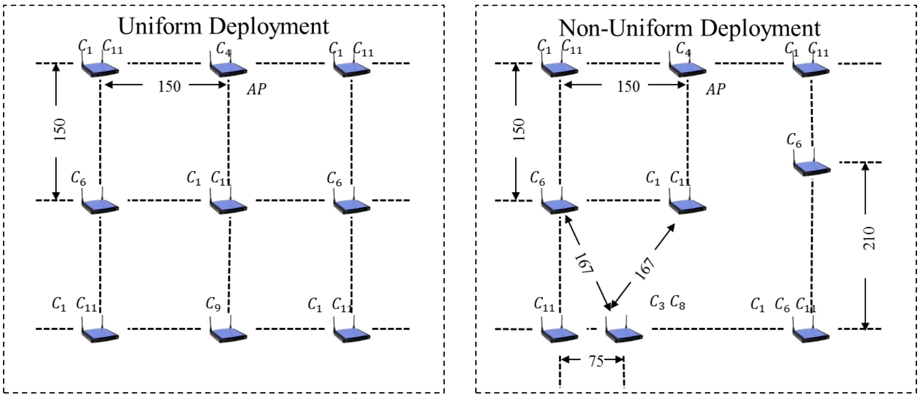
We assume a number of APs of similar capabilities regarding transmission power, the interference ranges and the number N of radios. We assume a high user density so that the uplink traffic from users to APs is delayed. Under such a traffic model, we can consider the uplink throughput without analyzing the interference among users. APs are selected according to their distance.

We model this scenario as an optimization problem with the objective of maximising the overall uplink throughput in a 1-dimensional network. Let $x(m)$ be the distance of the m^{th} AP from the leftmost AP. We define a binary variable c_i^m to indicate the state of AP as

$$c_i^m = \begin{cases} 1 & : \text{ AP } m \text{ transmits on channel } i, \\ 0 & : \text{ otherwise.} \end{cases} \tag{1}$$

Since the uplink transmission from users to APs is congested, we can generalize the objective as maximizing simultaneous transmissions by n APs on M channels (e.g. 11 channels in 802.11b) as

$$\sum_{i \in \{1,\ldots,M\}, m \in \{1,\ldots,n\}} c_i^m \tag{2}$$



(a) Optimal uniform deployment of APs (b) Optimal non-uniform deployment

Fig. 3. Communication channels assigned for two possible deployments of 9 APs and a given interference vector.

Some network constraints have to be met to achieve this objective.

First, if channel j is assigned to the m^{th} AP and active, other channels that have some spectrum overlap with channel j can not be assigned to the m^{th} AP. The set of channels overlapped partially or fully with channel i can be donated as $POC(i) = \{max\{1, i-T+1\}, \ldots, min\{M, i+T-1\}\}$, where T is the minimum separation for two orthogonal channels. For example, in IEEE 802.11b standard, $T = 5$ and for channel 3, $POC(3) = \{1, 2, 3, 4, 5, 6, 7\}$. Then the orthogonal constraint can be expressed as

$$\sum_{j \in POC(i)} c_j^m \leq 1, \forall i \in \{1, \ldots, M\}, \forall m \in \{1, \ldots, n\}. \tag{3}$$

In addition, the number of channels on each AP should not exceed the count of radios N equipped in the AP

$$\sum_{i \in \{1,2,\ldots,M\}} c_i^m \leq N, \forall m \in \{1, \ldots, n\} \tag{4}$$

Because these transmissions are active at the same time, they have to be beyond the interference range of each other as expressed in the constraint 5.

$$\begin{aligned} \left| c_{i+t}^p x_p - c_i^m x_m \right| \geq IR(t) c_{i+t}^p c_i^m, \forall m \in \{1, \ldots, n-1\}, \forall p \in \{m+1, \ldots, n\}, \\ \forall t \in \{0, \ldots, T-1\}, \forall i \in \{1, \ldots, M-t\} \end{aligned} \tag{5}$$

Finally, all APs should cover the whole area in order to provide the communication service to all users as

$$0 \leq x_p - x_{p-1} \leq 2R, x_1 \leq R, L - x_n \leq R, \forall p \in \{2, \ldots, n\}. \tag{6}$$

Here, R is defined as the communication range and L as the maximum distance between any pair of APs.

In summary, the optimization problem can be formulated as a non-linear programming problem with equation 2 being the objective and equations 3–6 being the constraints. However, although an optimal solution always exists, it is impossible to attempt to optimize the objective by solving the formulation. Given the number of APs, the network area and other network parameters, there must be an optimal solution, which consists of two parts. They are positions for every AP and channels on APs. Even though we know the first part, the optimal positions for APs, the time complexity for solving the maximization problem to obtain the channel assignment is

$$[(n-1)!]^{M-1} + [(n-1)!]^{M-1} +, \ldots, [(n-1)!]^{M-T} = O[(n!)^M] \tag{7}$$

Therefore, the time complexity for the original problem is greater than $O[(n!)^M]$.

4 Proposed Channel Assignment Technique

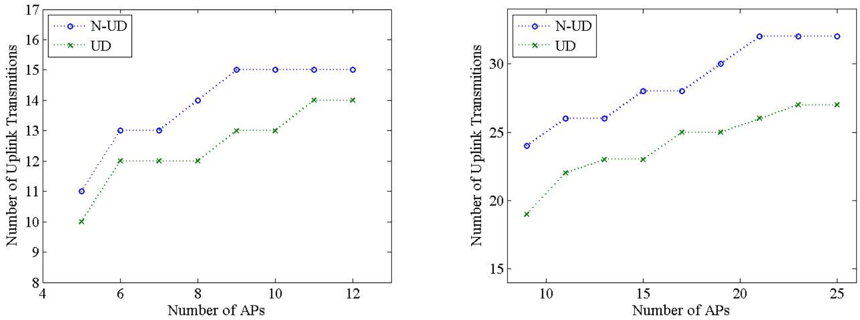
The hardness result in Section 3 provides a compelling reason to investigate heuristic approaches. In particular, we propose a polynomial time greedy algorithm that is able to find a good solution. An optimal solution constitutes locations for every AP and their channel assignment. Since these aspects are not independent, we propose a metric combining them. We define this metric as the channel coverage $CC(x_m) = Num_{ort}(x_m)/(x_m - x_{m-1})$, where x_m is the position candidate for an AP, x_{m-1} is the position of the current AP deployed in the last loop and $Num_{ort}(x_m)$ is the maximized number of orthogonal channels that can be assigned to the AP at the position x_m.

We propose a greedy algorithm to determine AP deployment and channel assignment (algorithm 1). Initially, parameters, such as the interference vector, communication range, dimensions of the placement area are configured (row 2 in algorithm 1). The algorithm then checks whether there are sufficient APs to cover the whole area (from row 3 to row 6). Then, we deploy the first AP and assign channels 1, 6 and 11 (the maximum possible channels). Next, we calculate candidate positions for every channel (from channel 1 to channel 11 in IEEE 802.11b/g standard). Channels with identical candidate locations are grouped (row 13 in algorithm 1). If one group (within the dimensions of the placement area) with the maximum number of channels is found, an AP is deployed there and assigned the channel group $CC(x_{m+1})$. Otherwise, the current number of APs is optimal with respect to the dimensions of the placement area (from row 14 to row 21).

In the case that after the last AP is placed, still not the complete scenario's dimensions are covered, we shift the last APs iteratively to fill the gap on the 1-dimensional area until the complete area is covered (from row 23 to row 45). The first AP is a special case (from row 39 to row 41).

Algorithm 1 Proposed Non-Uniform Deployment Algorithm

```
Initial State
initial Interference Vector (IV), communication range (R), line length L and other perimeters;
if L/R > (n + 1) then
    There is no enough AP to cover area.
    return;
end if
deploy the first AP and assign channel;
m=1;
for each m ∈ [1, n] do
    for channel j ∈ [1, NUM_CHANNEL] do
        calculate the candidate position for channel j;
    end for
    divide candidates into groups, each group includes channels that are assigned at the same position;
    find the maximized CC(x_{m+1});
    if position x_{m+1} exist then
        deploy AP at x_{m+1};
        assign channel to the (m + 1)^{th} AP;
    else
        m is the maximized number of AP that be able to be deployed in the area;
        return;
    end if
end for
m = n;
if x_m + R ≤ L then
    while m ≥ 2 do
        if m == n then
            x_m = last_position − R;
        else
            x_m = last_position − 2R;
        end if
        assin channel 1, 6, 11 to the AP at x_m;
        if x_m − x_{m−1} ≤ 2R then
            return;
        else
            last_position = x_m;
            m = m − 1;
        end if
    end while
    x_1 = x_2 − 2R;
    assign channel 1, 6, 11 to the AP (at x_1);
    return;
else
    the n^{th} AP covers the area;
    return;
end if
```



(a) Comparison of UD and N-UD performance with a 1000m placement area

(b) Comparison of UD and N-UD performance with a 2000m placement area

Fig. 4. Simulation results for 1000m and 2000m placement areas

5 Performance Evaluation

To demonstrate how non-uniform deployment for APs can be used to improve network capacity, we explore maximized simultaneous uplink transmissions as the metrics to evaluate the performance of our model and our proposed algorithm. In particular, we compare the algorithm with the uniform deployment of APs for varying number of available nodes and varying dimensions of the placement area. For the uniform deployment, we assume that the first AP is placed at one end of the deployment area and the last AP at the other end. In order to study the uniform deployment (UD), we set the distances among all APs in our model as identical. This problem can then be solved by "brute-force"in Lingo [12] when the number of nodes in the model is less than 30.

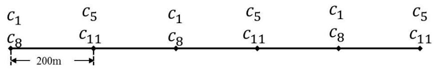
Apart from UD, we consider non-uniform deployment (N-UD) and the traditional channel assignment (UD-OC) employing orthogonal channels (namely channel 1, 6 and 11 in IEEE 802.11b/g standards).

Fig. 4(a) plots the maximized number of uplink transmissions achieved by N-UD and UD when the length of the placement area is 1000 meters, the valid communication range is 150 meters and the interference vector is

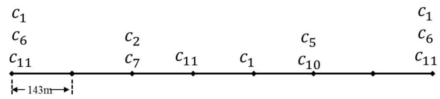
$$[300 \quad 280 \quad 230 \quad 170 \quad 70 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0].$$

In order to cover the whole line segment, we have to deploy at least 5 APs. As the figure shows, when the node number is relatively small (5 to 7), there is, in compliance with the paper [11], just a minor improvement for N-UD over UD. With higher AP density (8-9), the interference greatly increases, with negative impact on simultaneous uplink transmissions while in contrast N-UD can make full use of the spatial freedom and performs much better than UD.

Also, as more APs are added into the environment, there is no improvement for N-UD because the optimum number of APs that can be deployed in the



(a) Six APs placed in uniform distance and their available channels



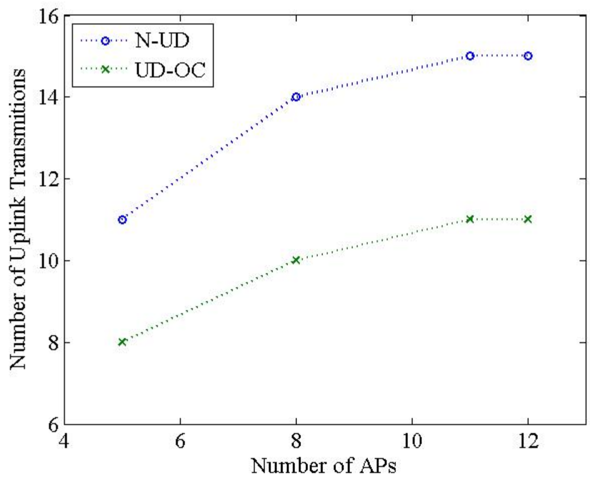
(b) Eight APs placed in uniform distance and their available channels

Fig. 5. Some performance in uniform deployment for different numbers of APs when the line length is 1000 meters.

area is 9. On the other hand, with UD it often happens that there will be no improvement by increasing the number of APs as the example shown in Fig. 5.

In Fig. 5(a), there could be 12 uplink transmissions in total. However, by adding one or two further APs would not increase the performance as shown in Fig. 5(b) since the distance among APs is fixed and therefore does not provide any optimization potential. Comparable results here achieved for a 2000 meter placement area as shown in Fig. 4(b), in which N-UD also outperforms UD and shows the similar performance with Fig.4(a).

In addition, we compared N-UD and UD-OC in Fig. 6 for 1000 meter placement area. Note that there are fewer channels in UD-OC than POCs, it shows worse performance in UD-OC than others.



(a) 1000 meters placement area

Fig. 6. Comparison result between non-uniform deployment and uniform deployment for 1000 meter placement areas.

6 Conclusion

In this paper, we considered the non-uniform deployment for APs employing POCs in Wi-Fi networks to improve network capacity. We provided an analytical model, derived its non-polynomial time complexity and proposed an alternative greedy polynomial heuristic for AP deployment in this setting. Our conducted simulation results reveal that the scheme gains capacity improvement over uniform deployment, e.g., along the subway platform. Future work will extend the work to two-dimension areas.

7 Acknowledgement

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