A Study on Deployment Strategies of Wireless Mesh Network with Partially Overlapped Channel Assignment

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To My Family

Abstract

Wireless Mesh Networks can accommodate users with high-speed wireless access to the Internet over a geographical area. The increasing growth for the demand on the network rate, but in contrast, via the limited unlicensed spectrum resource, leads to an over-crowding network with poor performance for users. Since dense network can result in, on the one hand, inter-cell interference, and on the other hand, better spectrum utilization, it becomes a critical issue for the network deployment in the phase of network planning.

In the existing literature, researched mainly focused on dense network by planning density of Access Points (AP) with only a small number of orthogonal channels from the given spectrum, in which the RF spectrum resource is not utilized efficiently since the other Partially Overlapped Channels (POCs) is wasted. For other POC assignment related works, they only restrict themselves to inter-cell interference mitigation without network dimension consideration. Even using the optimal POC assignment, poor network performance is deemed to occur for very low or very high dense networks. Determining the density of APs with POC assignment is still an open problem.

In this thesis, we study the joint issue of AP density and POC assignment that can provide the maximal network capacity in the given area. In doing so, we first present a novel scheme of POC assignment for the general POC model, and then the feasible region of AP density is derived, consisting of the lower bound and the upper bound of density. The network capacity is proved to decline with density greater than the upper bound and the optimal density of APs can be obtained by searching in the feasible region by means of proposed POC assignment.

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Chapter 1

Introduction

1.1 Background to Wireless Mesh Networks

Wireless Mesh Networks (WMNs) [1, 2] have become a promising design paradigm for high-bandwidth wireless access to the Internet due to its features of self-configure, self-healing, easy maintenance, simplicity and so forth. Potential application scenarios for WMNs include broadband home networking, building networking, community and neighborhood networking, public safety and security systems, intelligent transportation systems, and so forth, due to its considerable advantages including lower upfront investments, customer coverage, fast deployment and reliability.

In a traditional two-tier WMNs as depicted in Fig. 1.1, an access tier consisting of communication links between mesh router/access points (MRs/APs)

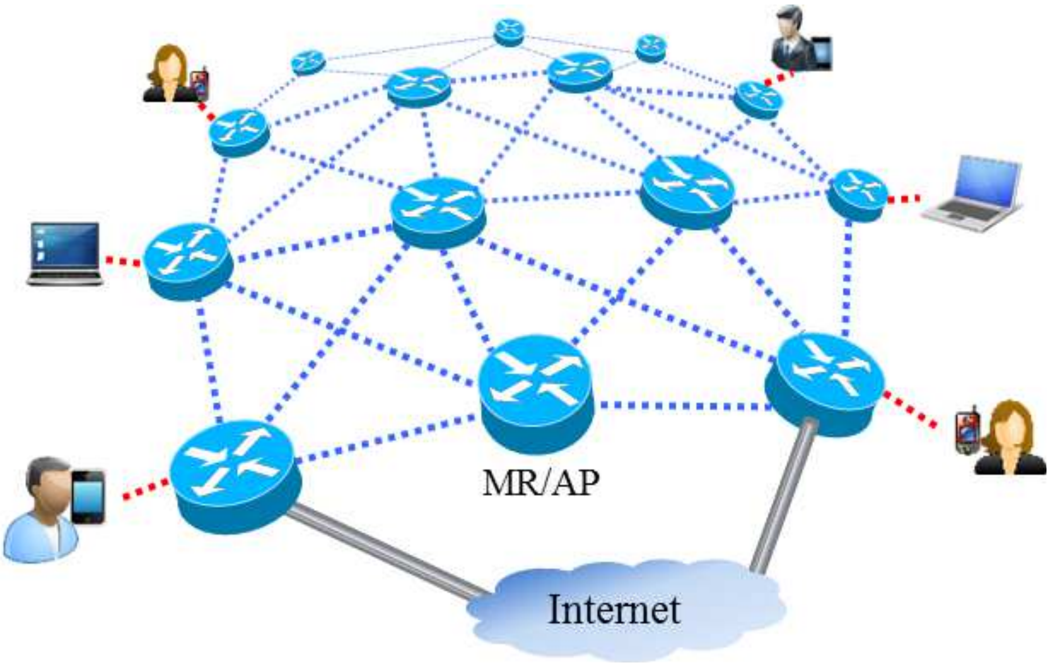


Figure 1.1: Wireless Mesh Networks

and users provides a wireless access, and a backhaul tier consisting of mesh nodes such as mesh routers and gateways forwards data traffic from access tier to the Internet. Evolution of wireless mesh networking technology has to deal with challenging architecture and protocol design issues, and there is an increasing interest on this technology among the researchers from both academia and industry.

Conventionally, APs and their associated users in access tier operate in the unlicensed industrial, scientific, and medical bands (ISM) at 2.4 GHz (red dash line in Fig. 1.1). One of most popular access specification in

MAC layer is IEEE 802.11b/g [3], in which an AP communicates its users (the AP and its associated users form a communication group, namely, a cell) using the same channel by means of mechanisms in MAC layer, such ass distributed coordination function (DCF) [4], point coordination function (PCF) [5], hybrid coordination function (HCF) [6] and so forth. Due to a limited number of channels in the frequency span, neighboring cells may use the same channel, which degrades significantly network performance. Therefore, in our work, we consider the impact of density of APs in the access tier since they can be very detrimental to the network performance. First, they provide access service to users. Furthermore, the traffic in the backhaul tier comes from APs. In addition, APs can also be as mesh routers with the advent of technology. Thus, the network capacity has a significant dependence on network design for access tier. In order to provide the optimal network performance in the access tier, a number of deployment strategies are raised and can be grouped into two broad categories:

Measurement Driven Methodology The network designer draw the complete map of the service area by investigating the signal environment. In such a manual site survey, network designers typically obtain area planning and mark areas with measurement of signal strength.

Similar to measuring physical signal situation, another operation is that the candidate locations to APs are selected since the physical locations of APs are restricted to particular areas, such as the connection to the wired LAN, the power supply, the installation and administration costs, and etc., in testbeds and commercial installations. Then, APs are deployed according to the signal environment measured in a prior approach to interference characterization. The methodology is accurate but with low scalability since it is costly and time-consuming depending on the size of the deployment and requiring extensive measurement.

Probabilistic Methodology Treating the network as a snapshot in the whole Euclidean plane or space and assuming the locations of given users as the realizations of some distribution, plan APs in particular following some distribution. This methodology is easy to model, but little is known about user distribution in the phase of network planning. The most popular model for IEEE 802.11 networks reported in [7], leading to many applications and extensions [8–10], is one of useful tools in probabilistic methodology to analyze performance for multi-cell networks.

In the phase of network planning for access tier the network performance can be improved by deploying more APs to provide more access opportunities for users. However, the dense networks in access tier also result in high inter-cell interference which has been referred to one of main sources to degrade network performance since wireless devices usually apply the same spectrum frequency span, such as in 2.4 GHz channel band for IEEE 802.11b/g. In order to mitigate inter-cell interference, using multiple channels has been cited as an effective approach, such as 3 orthogonal channels in IEEE 802.11 b/g. For orthogonal channels it is also easy to maintain channel assignment due to their orthogonality in frequency [11, 12].

However, it is still a waste of frequency resource for using only a small number of orthogonal channels among POCs, which have some overlapping frequencies for adjacent channels. It has been proved that POCs can improve the network capacity dramatically, especially in high density of networks [13]. But it is not straight-forward to maintain channel assignment due to the complexity of their interference model. Motivated by the aforementioned reasons, extensive researchers presented solutions from perspective of graph theory [14], ranking technique [15] and so forth[16]. Though these works can perform closely to the optimal result, they did not take into consideration the impact of network density. The service performance provided by deployed networks degrades for very low or very high dense networks. For relatively low dense networks despite the inter-cell interference becomes less harmful, the reuse of spectrum resource is low, resulting in low network capacity. On the other hand, one can expect benefits in spectrum reuse in some amount by scaling AP density, but it also scales inter-cell interference substantially in high dense networks. Hence, it calls for deployment strategies on density of APs and POC assignment that are provisioned in the phase of network planning.

1.2 Challenging Issues and Open Problems

In the proceeding section it provides a brief introduction to the recent developments in deployment strategies. These technology has to deal with challenging architecture and protocol design issues. The major issues related to AP planning and POC assignment include:

1. General description of POCs: POC model, refereed to POC distribution in the range of spectrum and interference model among them, is the foundation of POC assignment. Although existing researches have done to address POC assignment regarding the given specific POC model, it requires a general description of POCs for a higher scalabil-

ity.

2. Scheme of POC assignment on the basis of general description of POCs: Though a number of works are devoted to POC assignment, in particular, the scheme of POC assignment on the basis of general description of POCs is need. Since it is a NP-hard problem for POC assignment, the discussion on the optimality should be given.

3. The impact of AP density on network performance with POC assignment: While using a single channel or just orthogonal channels, the impact of AP density on the performance of network capacity is easy to analyze. However, it is not straight-forward for the case of POCs. Furthermore, since user distribution varies with time and is hard to obtain in the phase of network planning, the deployment strategies is need to optimize the wireless service in the deployed area without the information of user distribution.

4. Joint design of AP density and POC assignment: The network capacity can be improved by deploying additional APs in a geographical area since the expected distance from users to the associated APs becomes shorter. Meanwhile, inter-cell interference also increases with the number of APs and substantially in the high dense networks. In order to

provide the maximal network capacity over a geographical area, the joint issue of AP density and POC assignment needs to be addressed.

In addition, other topics, which are not studied in this work, include challenges and issues in designing medium access control and routing protocols for WMNs, security, and etc. According to this discussion, the need for the deployment strategies for AP density and POC assignment in the WMNs is evident.

1.3 Research Objectives

In this thesis, the overall objective is to provide deployment strategies for AP density and POC assignment for the access tier in WMNs. In the first step, we will present a general description of POC model, including the total number of overlapped channels, the number of orthogonal channel, and interference degree among channels, so as for a high scalability of the proposal. In order to calculate the interference without information of user distribution, we will use the deterministic methodology and the worst case, that the severest inter-cell interference occurs. According to the POC model, we will study an optimization problem of POC assignment to minimize the cumulative inter-cell interference and propose a novel approach to POC assignment.

Furthermore, we will concentrate ourselves on the impact of AP density with POCs on the performance of network capacity. We will first to show given the number of APs the existence of the upper bound of network capacity, and the existence of the lower bound of network capacity that the optimal POC assignment can achieve at least. From these conclusions, we will derive the feasible region of density of APs consisting of lower bound and upper bound of density of APs. It will tell us first that the network capacity will definitely decline for deploying an amount of APs greater than the upper bound. Also, the optimal density of APs lies in the feasible region. And we will also validate our conclusion from numerical results.

Based on the analysis of the feasible region of AP density, we will propose the algorithm for deployment strategies for the optimal density of APs combining with the proposed POC assignment with different POC configurations.

1.4 Thesis Outline

We organize our work in five chapters. The content of this thesis is outlined as follows:

Chapter 1. Introduction:

In this chapter, we gave a brief introduction to the background of our research. We also discussed the challenging issues and open problems in the existing development of related work. Finally, We showed our research goal for this research.

Chapter 2. Overview of Deployment Strategies:

In this chapter, we introduced the related works for the deployment strategies and the overview of our proposal in this thesis. We started by adopting a deterministic methodology to model the AP deployment for network planning as cellular-like networks. We then introduced the feasible region of AP density and the overview of its analysis process.

Chapter 3. Novel POC Assignment:

In this chapter, we concentrated ourselves on the POC assignment. First, we gave the related works and motivation for proposing our novel assignment scheme. Then, the general POC model including channel interference model is provided so as for the high scalability. To void the impact of lack of information of user distribution on the deployment strategies in the phase of network planning, the worst case is applied, in which the severest inter-cell interference occurs. Then, according to the given POC model, we considered the optimization problem of POC assignment and the approach to solve the problem in details. Finally, we validated our proposal from our numerical results.

Chapter 4. Joint Design for Deployment Strategies:

In this chapter, we mainly restricted ourselves on joint design for deployment strategies of AP density and corresponding POC assignment. We first proposed the algorithm for the optimal AP density with the prior knowledge of feasible region of AP density. In the algorithm, it searches for the optimal AP density in the feasible region using proposed POC assignment. In doing so, we explored the features of POCs in the deterministic deployment for the upper bound of network capacity and lower bound of network capacity. From these results, we derived the feasible region. Finally, we showed the deployment strategies in our results.

Chapter 5. Conclusion:

In the final chapter, we summed up our thesis and discussed the extension for future works.

1.5 Thesis Contributions

In this thesis, we studied the POC assignment and deployment strategies for the phase of network planning. The main contributions of this thesis are summarized as follows:

- We provided a comprehensive introduction to the recent developments for network design, including background of wireless mesh networks, the opportunities and challenges of deployment strategies, and discussed the need for the recommendation of joint design of AP density and POC assignment.

- We first developed a general POC model to depict the POC distribution in the given spectrum span. It showed the relationship between the number of orthogonal channels and the total number of POCs. It also defined the interference among POCs. With the help of POC model, we proposed a scheme of POC assignment from a novel perspective: to choose POCs according to their center frequencies. In the proposal, it also tells the upper bound of network capacity given the AP density. Though the problem of the optimal POC assignment is NP-C problem, the upper bound of deviation of the proposal from the optimal result can also obtained. Numerical results illustrated the effectiveness of our proposal in the string deployment and the hexagonal deployment.

- We further analyzed the feasible region of AP density and concluded that the network capacity decreases with AP density greater than the upper bound and the optimal density lies in the feasible region which consists of lower bound and upper bound of AP density. Thus, we can design the algorithm by means of the proposal POC assignment to find the optimal result in the feasible region. Since the lower bound of AP density is easy to obtain, the main work is to produce the upper bound of AP density. To analyze the existence of the upper bound of AP density, the lower bound and the upper bound of network capacity in the given deployment area are derived, from which we derived the result. Finally, we used the numerical results to validate our proposal and to show the deployment strategies as well as the impact of POC configuration.
- We also examined the extension for our current work by consideration of new challenges related with POCs.

Chapter 2

Overview of Deployment Strategies

2.1 Introduction

Simplicity, scalability, load-balancing and high data rate would be required for efficient communications for wireless mesh networks. Network design of high performance is a grand research challenge in conjunction with specific scenarios, such as military battle field and network recovery from natural disaster. In order to provide a good service to users, a number of deployment strategies [17] should be optimized, including AP density, channel assignment for APs, configuration in MAC/Routing layers [18], and so forth.

In our thesis, we address the scalability issue in wireless mesh networks from the network deployment perspective. We focus on AP density and corresponding POC assignment in the access tier in WMNs since they fundamentally limit the performance of other aspects. This chapter briefly covers some knowledge of our analysis. We first provide a comprehensive discussion to the recent developments related to the deployment strategies. We do this to recognize the limitations of existing solutions. Then we introduce our deterministic approach for network planning that is regular hexagonal deployment for APs with POCs. Finally, we give an overview of WMNs in access tier with the context of POC assignment.

2.2 Related Work

WMNs have emerged as one of the most promising techniques for self-organizing and auto-configurable wireless networking to provide adaptive and flexible wireless Internet connectivity to mobile users. The state-of-the-art achievements in the area of protocols [19, 20] and architectures [21, 22] for WMNs in different universities and industrial research labs have given a boost to its expansion. Techniques that solve deployment problems [23, 24] for access tier usually can fall into two broad categories: measurement driven methodology and probabilistic methodology.

In measurement driven methodology [25–28], it usually performs a site measurement to determine the best placement and configuration of APs.

They take extensive RF measurements at different locations of the site to obtain floor plans of the building. This process, though precise, but very complex and low scalability depending on the deployment size. Studying large-scale wireless networks by means of simulations and experiments is both expensive and time-consuming. It is, therefore, significant to establish an analytical understanding of such networks in order to look insight into the system dynamics.

The approaches [29–31] based on candidate positions for APs can also grouped into this category. They apply a combinatorial selection from a set of candidate positions and run an optimization of an objective function given weighted information for each location. This has also been done only at the initial step to obtain the environment measurement. Though this method has real statistics, it cannot determine the optimal density of APs in the sense that it is usually regarded as (0-1) allocation and can be seen as a NP-complete problem. The problem of the base station positioning is considered in [32, 33] , and also proved that the problem is the NP-hardness. More general model for networking deployment is studied in [34] by taking multiple objectives including available budget, throughput requirement and coverage range into consideration. These works can be usually grouped into $(0-1)$ assignment without intensive penetration into networks.

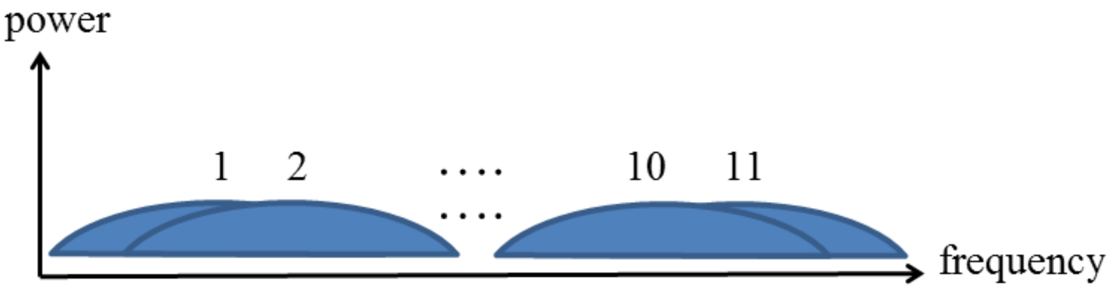
The most related architectures [35, 36] with our proposal referred to cluster-based wireless mesh and ring-based wireless mesh for dense urban coverage and wide-area coverage scenarios, respectively. In a cluster-based wireless mesh, multiple adjacent APs, which are connected by means of wireless channel, form a cluster. The ring-based wireless mesh is based on a mesh cell architecture where the cell is divided into several rings allocated with different channels. They provided a mixed-integer nonlinear programming (MINLP)-based optimization proposal to find the optimal deployment strategies including AP density. One interesting finding in their numerical results shows that there exists an optimal value of the number of APs which maximizes the objective function. However, they are primarily devoted themselves on the impact of backhaul tier on the network performance. In comparison with our proposal, we mainly focus on the access tier by assuming no limitation on relaying traffic among mesh routers or APs.

In the probabilistic methodology since the landmark of Bianchi [7] which provides an exactly accurate model to predict the throughput performance for the network with only one AP, a number of works have being addressed other issues [37–39], using the similar approach we called probability methodology. It is useful to analyze the network performance given the detailed information such as user distribution, mobility model and so forth. Balachandran *et al*. [40] studied the impact of user behavior, including user distribution, user session duration and user data rates on the network performance. Literatures [41, 42] presented network throughput in the presence of hidden terminals which is one of reasons degrades the performance of wireless networks.

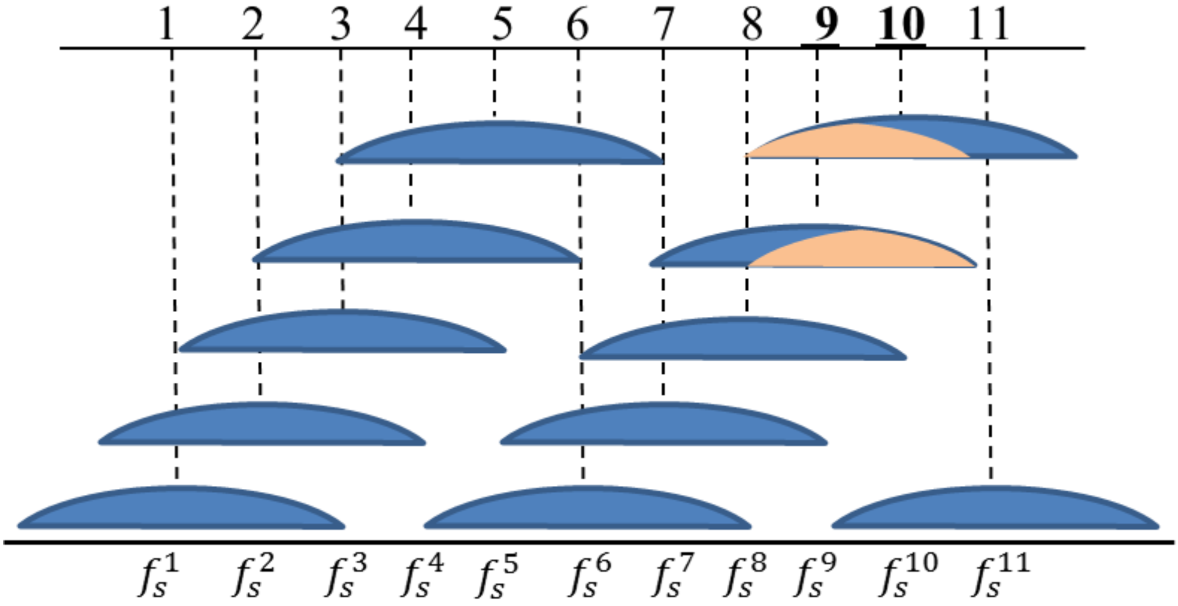
In addition, probabilistic methodology can be applied for the analysis of multiple APs/cells. Panda *et al*. [10] used this method to model multi-cells with application to channel assignment and Ozyagci *et al*. [24] investigated the impact of cooperation based on locally available information shared among multiple APs on the network capacity. However, all these studies first statistically focused on the analysis of the network performance given all knowledge, such as user distribution, AP distribution, and channels assigned to APs, and so forth. Then they derived the impact of some aspects. Though they are accurate in the analysis, knowledge of the network configuration, especially for the user distribution, is hard to obtain in the phase of network planning, and the analysis of statistic snapshot cannot tell the optimal configuration.

Another fundamental issue is channel selection for multiple APs to reduce inter-cell interference. The 802.11 work-group currently documents use for WLANs in the distinct frequency span in 2.4 GHz [43]. It is divided into a multitude of channels. For example, there are 11 channels distributed in the spectrum band used in North America as illustrated in Fig. 2.1a. Each sector represents a channel in the domains of frequency and power. The index at the top of a sector is the channel index. In order to make explanation easier, we use the alternative in Fig. 2.1b to describe POCs. Traditionally, we can use the degree of overlapping frequencies to describe the interference between two channels as illustrated in brown in Fig. 2.1b. Thus, links using the same channel or partially overlapped channels, such as channels 1 and 3, interfere with each other if they are in their interference range. With sufficient frequency separation, there will be no interference, for example, between channel 2 and channel 8. It also shows that for each channel i, it corresponds a fixed center channel frequency f_c^i, which is the characterization in our proposed POC assignment.

Conventionally, we can use a single channel at home or in a small office, for example, and it is enough to provide access service for users. For the scenario with a single channel, it is easy to model and recommend deployment strategies. But due to the broadcast nature of wireless signals, the inter-cell interference is strong in high density of APs, which leads to a bad



(a) POC Distribution in Frequency Span



(b) Alternative Description of POCs

Figure 2.1: Description of POCs (copyright © 2015IEEE)

network performance. To improve the network capacity, one of effective methods is to use orthogonal channels [44, 45]. Due to orthogonality among them, it is not too hard to maintain channel assignment, statistically or dynamically according to user distribution, signal strength, and so forth. However, we still do not make the best full use of channels since there are still some channels unused besides orthogonal channels. And it has proved that a good design of POC assignment can lead to significant improvement in spectrum utilization and network performance compared with only using orthogonal channels [13, 14, 46, 47].

However, due to complexity of POCs it takes more effort to maintain POC assignment. In [48], the authors measured the interference between different APs when POCs are used from engineering perspective of the physical characteristics of the communication. Since the hardness to measure the interference degree among POCs, most of existing works use the fixed POC interference model in [13, 49, 50] as shown in Table 2.1. The term channel distance between channels i and j refers to distance between their channel center frequencies, and equals $|i-j|$. As discussed above, the channel interference degree with channel distance of 0 is 1, and channel distance greater than 5, there is no channel interference. For channel distance between 0 and 4, the channel interference degree is between 0 and 1, namely,

Channel Distance	0	1	2	3	4	5-10
Interference degree	1	0.96	0.77	0.66	0.39	0

Table 2.1: Example of channel interference

partially overlapping between them.

By means of fixed POC interference measurement, Mishra *et al*.[13, 50] systematically modeled the POC based network design and discussed several approaches to adapt existing protocols to use POCs. Their discovery showed that POC based design can improve network capacity up to three times in the IEEE 802.11b/g based networks compared with using only the orthogonal channels. In addition, some works characterized the problem of channel allocation aiming at minimizing the interference, mostly from the viewpoint of graph theory, such as graph-coloring problem [51, 52] and directed graph [53]. A graphical game and uncoupled learning based distributed POC assignment is proposed in [54] in the absence of information exchange. Unlike traffic-free based schemes, load-aware based approaches assuming known traffic profile [49, 55–57] or dynamic traffic [51, 52, 58] in the network aim at minimizing cumulative network interference.

Cui *et al*. [16] presented a new interference model characterizing both the signal impact from POCs and the physical distance between two APs.

They first defined 'node orthogonality' model taking into account both the physical distance and POC separation. Then, they proposed an algorithm to approximately minimize the cumulative interference for throughput optimization. Mohsenian *et al*. [59] presented a mutual interference model for all channels as an extension to SINR model for POCs by introducing channel overlapping matrix to systematically model the overlapping of POCs. From the analysis it concluded that interference range of receiver of communication depends on channel separation of that communication to its neighboring communication only. Based on the interference information of channels, it formulated channel allocation as a linear programming formulation. The interference model proposed in [53] describes relationship between two channels as a binary variable. Two links will interfere with each other if their distance is less than the pre-defined interference range, and otherwise not. This model did not offer insight into features of POCs in depth, since it is a general model as used in orthogonal channels.

One limitation among other relevant research works is that they formulated POC allocation solely as (0-1) optimization to study the improvement using POCs compared with the orthogonal channels. Mathematical formulation for POC allocation to optimize the network performance, however, just gave the necessary condition of optimization. Feng *et al*. [46] modeled

POC allocation into a linear mixed integer problem (MILP), first relatively hard to be extended to large-scale networks. Furthermore, they presented no discussion in depth on the impact of different network topology settings. The work also studied the density of APs with POCs and concluded that using POCs in the high density of APs can improve the network performance, however, without indication of the optimal density of APs. Moreover, it is impossible to apply the approach in the network planning in practice because the proposal considered irregular deployments (e.g., the random deployment).

Furthermore, it is notable that the existing works use their specific models [48, 50] to describe channel interference. Mishra. ***et al.*** [50] conducted experiments to measure channel interference among POCs, while Burton. ***et al.*** [48] calculated channel interference among Direct Sequence Spread Spectrum (DSSS) [60] modulated signal based on the given chipsets. It is easy to find obvious difference between their results, which gives rise to hardness to characterize common channel interference among POCs.

Moreover, these methods usually provide a way to assign channels to maximize the network capacity, without consideration of the optimal density of APs in the phase of network planning. We are motivated by our discussion that it also requires the knowledge of the topology of APs, including density

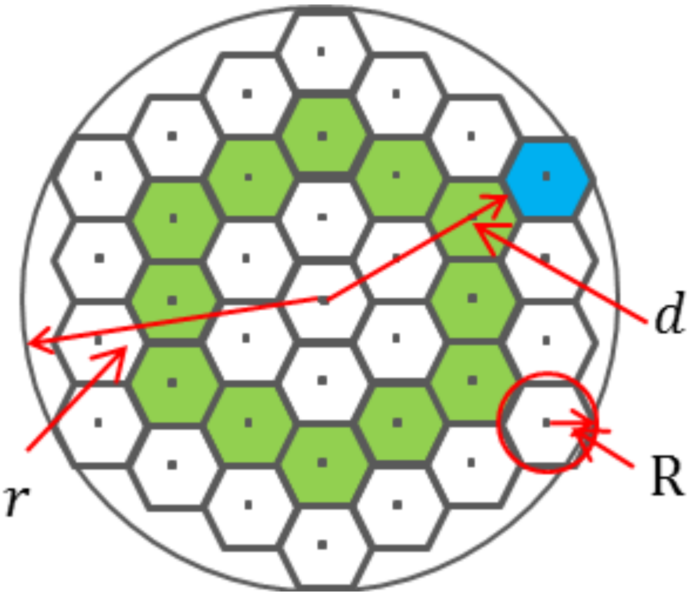


Figure 2.2: Hexagonal Deployment (copyright © 2015IEEE)

of APs, their location patter (ring, uniform, specific distribution, and etc.) to provide the best service to the user in the given area.

2.3 Overview of Proposal for Deployment Strategies for AP Density with POC Assignment

2.3.1 Deterministic Approach

Recalling from drawbacks in existing approaches in Section 2.2, we use a deterministic approach to model AP deployment by hexagonal deployment as depicted in Fig. 2.2. In order to avoid misunderstanding, we start by giving definition of interference range.

Interference Range [61]: The interference range is the range within which the transmitted signal cannot be decoded correctly by the receiver but is of sufficient power to disrupt the correct reception of other packets that the receiver can be receiving. This is in consistence with the traditional concept of interference range.

In our model [62, 63], we attempt to determine AP density and corresponding POC assignment in the area with radius of interference range r as illustrated in Fig. 2.2. We ignore the edge effected, which is said to occur when a user at the edge of the deploying area experiences less interference than those at the center of the area, since the interference range is determined by the transmitting/receiving power. Then, the number of APs in the interference range is:

$$\mathrm{f}(l) = 3l^2 + 3l + 1,$$

where l is the number of levels defined as the number of APs along the line from the AP at the center of the deploying area to the AP at the outermost, but except the AP at the center. In the figure, the number of levels is 3 and APs from the center are in 0-th, 1-th, ..., l-th level, respectively. For example, APs in green in the figure are in 2-th level. Thus, determining the optimal density of APs equals determining the optimal levels of APs. Then, we can use the concept of levels to describe the distance between two neighboring APs.

Distance between Two APs: AP_j is said to be k levels away from AP_i (or cell i) when AP_j (or cell j) is in k-th level assuming AP_i is at the center of the deployment area. For example, the cell in red circle is 3 levels away from the blue cell. We use distance between two APs/cells to calculate the inter-cell interference between their downlinks.

In each cell there are an AP at the center and its associated users conditioning on the fact that users always associate its nearest AP with the strongest signal power. Then we introduce the definition of communication/coverage range of an AP.

Coverage Range for an AP/Cell: The coverage range for an AP/cell is the range within which users always associate the AP. Despite an AP can sense and receive a signal from other cells, we say that its coverage range is still within limited area in accordance with association constraint. We use this concept to describe the coverage range from perspective of whole network with multiple APs/cells. It varies with the number of levels in the given area. The coverage area of a single AP within the given area is much larger than that with multiple APs within the same area.

As illustrated in Fig. 2.2, the coverage range approximates to R conditioning on the assumption that edge effect, some spots at the edge of the deploying area are not covered by any cell, is ignored, which is solely for modeling purpose.

To void the lack of information of user distribution on the deployment result since user distribution varies with time and is not available in the phase of network planning, we use the worst case to calculate the interference for the downlink evaluation, since downlink carries the dominating traffic in most of applications [64, 65]. The worst case is defined as follows.

The Worst Case: The interference from AP_j k levels away to AP_i occurs for the user nearest to AP_i at the edge of cell_j (AP_j) and the interference distance is $d = (2k-1)R$.

For example, the interference distance in the worst case from the blue cell to the center AP is $d = 5R$ in Fig. 2.2. Unlike the worst case to calculate the inter-cell interference, it is expected to be probabilistic or average for approaches based on stochastic process, such as Poisson Point Process [66, 67] which models AP locations as a specific distribution. As suggested by the term “worst”, we apply the severest case to calculate the inter-cell interference.

2.3.2 POC Model

The objective of POC assignment strategy is to ensure efficient utilization of POCs (e.g., by minimizing inter-cell interference). However, optimal channel assignment is a NP-C problem, similar to the graph coloring problem. Generally, POC assignment for APs should be performed in a way so that it satisfies the desired network performance. The works [13, 68] on POC assignment have grown quickly over the past years, mainly due to its benefit on mitigation of inter-cell interference over orthogonal channels. In the discussion of existing works, one of limitations is that they use the specific POC model, such as the example in Table 2.1. In our work, we provide a general POC model such that the scheme of POC assignment and proposal for AP density have a high scalability. In our model, we use $\left(B, \triangle_f, K, M\right)$ to describe distribution of POCs, where B is the channel bandwidth, $\triangle_f$ the channel shift between two neighboring channels, K the number of orthogonal channels at most, and M the total number of POCs. It shows that M partially overlapped channels uniformly distribute in the given spectrum span T_0. It can determine the POC configuration given any two entries out of the model parameters. In addition, to measure the interference degree $\mathscr{F}(i,j)$ between two channels i and j is linear with their overlapping frequencies based on our observation. The detailed mathematical formulation can be found in Section 3.

Most of existing POC assignment methods do not consider the feature of POCs. From Fig. 2.1b, it shows that assigning POCs to APs is equivalent to assigning channel center frequency. The above observation motivates us to take a different perspective on the modeling of POC assignment. We can see from our discussion in the section of related work that one of hardness of POC assignment stems from integer index (channel index) assignment. Correspondingly, in our proposal, we avoid assigning channel index by means of relaxing fixed discrete channel center frequency to continuous channel center frequency. On obtaining the temporary result of relaxed center frequency for each AP, place constraints to find the POC assignment by means of numerical technique. In this method, it first can avoid the hardness of POC assignment. In addition, it can derive the upper bound deviation of the network capacity for the proposal from the optimal result.

2.3.3 Feasible Region of AP Density

To supply the ever-growing number of users with demand of high data rate, wireless networks are inclining to dense deployments of APs [69]. However, as AP density increases, inter-cell interference from the same channels or partially overlapped channels becomes more intense since cell size becomes smaller and the number of channels is limited. Thus, the network performance might degrade with increased AP density [27]. Therefore, a good design and management are essential for achieving the benefits of dense deployments of APs. However, an analytical modeling for the density of APs with partially overlapped channels is still a challenging problem.

This work is concerned with analytical modeling of the optimal density of APs in conjunction with POC assignment. It has been shown that the problem is considered in [32, 33] to be NP-hardness. We attempt to find the optimal AP density in our defined reasonable network assumption, which can be seen as two steps. Our goal is to study the aggregate downlink performance using our deterministic approach with the context of POC assignment. In our analysis, we prove in first step that the network capacity decreases with AP density greater than upper bound, and thus, the opti-

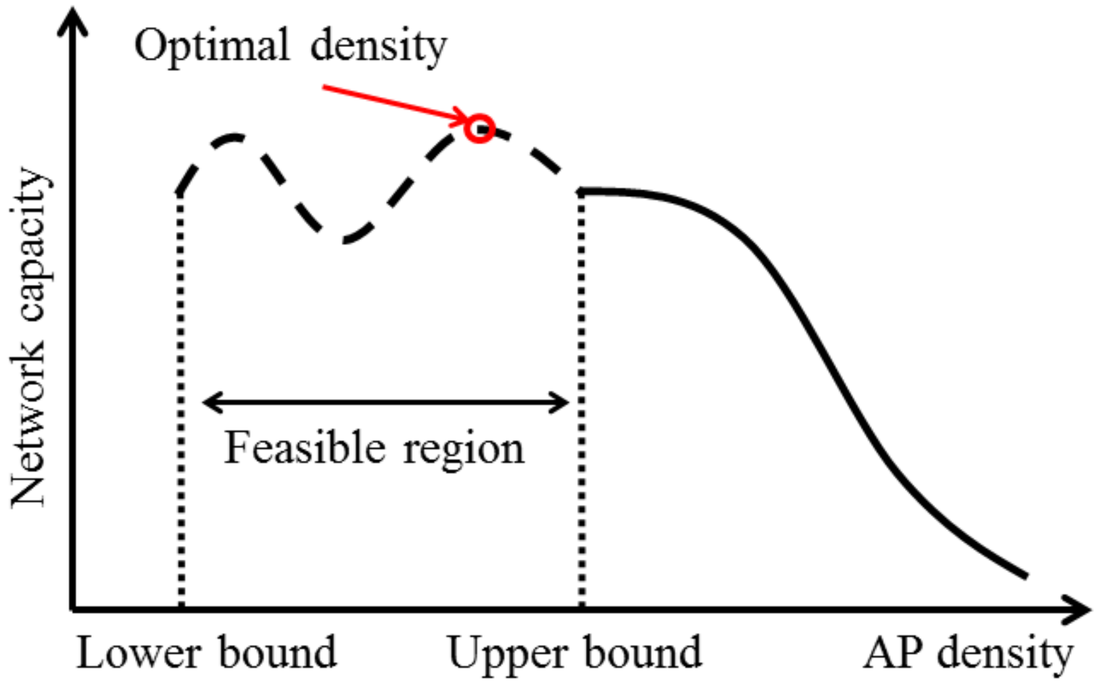


Figure 2.3: Feasible Region of AP Density (copyright © 2015IEEE)

mal density lies in the feasible region consisting of lower bound and upper bound as illustrated in Fig. 2.3. Analytical modeling can provide important insights to effective design, deploy and manage the multiple APs. Despite no knowledge for the exact close-form value of the optimal AP density, we can make less laborious for the final result. Consequently, from the result of analysis, in the second step we can design a simple algorithm to search for the optimal density of AP within the feasible region by means of our proposed POC assignment.

2.4 Summary

In this chapter, we have made a comprehensive survey on the state of the art in the deployment strategies for wireless mesh networks, and have described the major research issues in wireless mesh networks. Then, we have provided an overview of our deployment strategies for AP density, including deterministic approach to model AP deployment in cellular-like pattern, the worst case to calculate inter-cell interference among POCs. By discussing our motivation it enables an essential design for novel POC assignment and optimal AP density, in which one of primary work of the way to obtain the feasible region of AP density in the following chapters. Finally, we have shown an overview that the optimal density lies in the feasible region.

Chapter 3

Proposed Novel POC Assignment

3.1 Introduction

The popularity of cost-effective technologies for wireless access for mobile end users has influenced communicating and computing ways significantly, and has established perfect solutions for the deployment in scenarios such as in the home and small enterprise segments with limited coverage area and a few users. One interesting extension from existing works is to provide wide-area wireless access such as large-scale enterprise scenarios. Due to broadcast nature and limited number of wireless channels in IEEE 802.11, the inter-cell interference is the main obstacle to provide high-speed service to wireless end users. To scale the aggregate downlink capacity, one of key promising technologies is to employ POCs based on its better frequency utilization compared with only using orthogonal channels, as introduced in Section 2.2. We only study fixed POC assignment, i.e., static models where the set of connections stays stable over time in this work. Conversely, dynamic POC assignment or hybrid POC assignment addresses issues, where the demand for channels at the wireless node, including users, MRs and APs, varies over time.

The focus of this chapter first developed a general POC model from mathematical viewpoint including POC distribution and their interference model, and then explored features of POCs to propose the optimization model of POC assignment. At last, we validated our proposal by numerical results.

3.2 Definitions

3.2.1 General POC Model

The commercial success of the IEEE 802.11 wireless networking standard gives rise to more contention of frequency usage. The 2.4GHz ISM band is assigned spectrum in the order of 2400-2484MHz for multiple POCs. Current works suggest that only orthogonal channels used in the network are overly restrictive, which can be improved by applying all POCs across the spectrum. There are a number of papers focused on POC assignment, but without detailed description for POCs. To overcome limitations of existing works about POC assignment as discussed in Section 2.2, we developed a general POC model to describe POCs that is $\left(B, \triangle_f, K, M\right)$, where B is channel bandwidth, $\triangle_f$ the channel shift between two neighboring channels, K the number of orthogonal channels at most, and M the total number of POCs in given spectrum span T_0. The relationship among entries of the model is represented:

$$B + (M-1)\triangle_f = T_0 \tag{3.1}$$

$$(K-1)\left\lceil \frac{B}{\triangle_f} \right\rceil + 1 = M \tag{3.2}$$

$$M \geqslant K \tag{3.3}$$

$$K \in \mathbb{Z}^+ \tag{3.4}$$

Formulas (3.1, 3.2) in this model tell us that M channels are distributed uniformly in the spectrum span T_0 based on the way IEEE 802.11 divide the given spectrum band. Other literature also describes the POC distribution across the given spectrum implicitly in the same way. Formula (3.3) always holds since POCs contain these orthogonal channels. By means of our model, any of two entries of $\left(B, \triangle_f, K, M\right)$ can determine an instance of POC configuration. And in this thesis, we use $(M,\ K)$ to describe a POC instance. For example, given a spectrum span, we can divide it into 7 POCs with 3 mutual orthogonal channels at most: (7, 3), or 11 POCs with 4 mutual orthogonal channels: (11, 4). Then we can easily obtain that the channel bandwidth for (7, 3) is greater than that for (11, 4). In our evaluation, we will find the impact of POC model on the performance in different densities of APs. It follows that we can expect substantial network capacity by dividing the spectrum span into more POCs with smaller channel bandwidth in the high density of APs, whereas better benefits for fewer POCs with greater channel bandwidth in the low density of APs.

3.2.2 Channel Interference Model

In the prior section, we defined the POC model that POCs are uniformly distributed within the frequency span. From viewpoint of signal processing, a closely related notion refers to channel interference, which associates to the physical signal impairment to one channel due to interference from signal on adjacent channels. The theoretical channel interference is primarily determined by the filtered transmit (interfering) channel, the receiving processing gain, and the receiving filter response. However, the actual interference among POCs varies for different chipset and filter configurations. In existing works about POC assignment, they gave a specific description for channel interference, which results in hardness to find desired features of POCs. In our work, we can find in Fig. 2.1b that there is a corresponding standard center frequency (S-CF) f_c^i for each channel. It follows that $\triangle_f = f_c^{i+1} - f_c^i$. Thus, we use S-CF separation to describe the degree of channel interference. In our investigation for channel interference based on experiment measurement [48, 70], it can be fitted approximately into a linear function with S-CF separation. Based on this observation, to determine channel interference $\mathscr{F}(i,j)$ between channels i and j, we set a piecewise model:

$$\mathscr{F}(i,j) = \begin{cases} 1 - \frac{\left|f_c^i - f_c^j\right|}{B}, & \left|f_c^i - f_c^j\right| < B \\ 0, & \text{otherwise.} \end{cases} \tag{3.5}$$

In this model, the channel interference between two channels i and j is linear ratio of channel separation over channel bandwidth if they are overlapping in the frequency span as shown in Fig. 3.1; otherwise, there is no

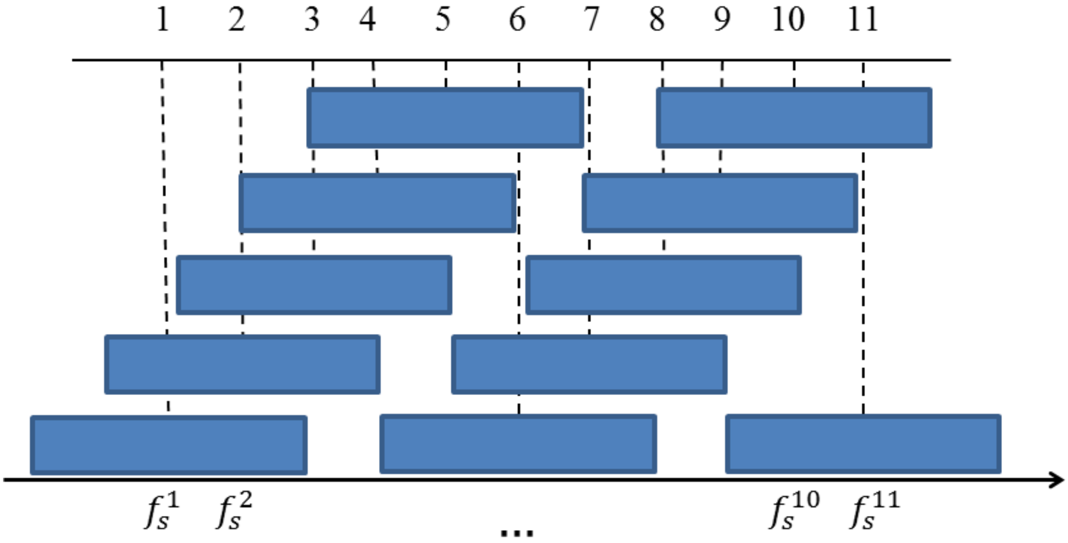


Figure 3.1: POC model

channel interference. Equivalently speaking, they are orthogonal channels. In comparison with field measurements, in which channel interference is measured through the on-site approach, our method has a greater scalability.

3.3 Proposed POC Assignment

3.3.1 Assumptions and Objectives

In order to combine the objective to determine the optimal density of APs in following Section 4, we assume that:

- Fixed number of APs are deployed according to the deterministic methodology as in Section 2.3.1 in the given area with the radius of interference range, though the scheme of proposed POC assignment can be extended into other deployments, such as irregular deployments. Thus, the set of APs are $\boldsymbol{\Psi} = \{\mathrm{AP}_i,\ 0 \leq i \leq \mathrm{f}(l)\}$, l is the given number of levels of APs in the regular hexagonal deployment.

- Another important assumption is only to consider downlinks from APs to users in access tier. Thus, there is no limitation on the traffic relayed among APs in routing layers in our assumption. We ignore the impact from routing layer among MRs/APs since we usually can study their influence separately, using different frequency spans, 2.4GHz in access tier and 5GHz in backhaul tier, as an example. Thus, our analytical model can be extended to incorporate with the routing layer by means of dealing with the limitation in routing layer as constraints.

- Furthermore, since user distribution varies with time, we calculate the inter-cell communication interference in the worst case as discussed in Section 2.3.1 without knowledge of user distribution. Another reasonable consideration on this assumption is that we study the downlink performance from viewpoint of Shannon theorem.

- We ignore border effect, in which less inter-cell interference might occur for cells at the border of deployed area due to fewer neighboring cells.

According to assumptions and channel interference model $\mathscr{F}(i,j)$, we can calculate communication interference between any two given cells in the deployment area. To focus on our proposal, we simplify the optimization model with the objective of minimizing the cumulative network interference without consideration of other aspects such as fairness among different communication cells.

3.3.2 Mathematical Formulations

As discussed in Section 2.2, one of hardness for POC assignment stems from assignment of integer channel index and usually can be formulated into MILP problem. From our observation that assigning channel index of POCs to APs is equivalent to assigning fixed standard channel center frequency (S-CF) corresponding to channel index, we first attempt to select a channel with relaxed channel center frequency (R-CF) by relaxing S-CF to continuous values in the frequency span:

$$\mathscr{F}\left(f^i, f^j\right) = \begin{cases} 1 - \frac{\left|f^i - f^j\right|}{B}, & \left|f^i - f^j\right| < B \\ 0, & \text{otherwise.} \end{cases} \tag{3.6}$$

In this step, we can simplify the model to solve the selection of channel center frequency for APs. Following the result, we place the constraint to find POC assignment from R-CF to S-CF.

First, we give some basic formulation in our model. We use a common model for signal propagation that the received power $\mathscr{P}(d_{ij})$ is:

$$\mathscr{P}(d_{ij}) = A d_{ij}^{-\beta}, \tag{3.7}$$

where d_{ij} is the distance between receiving and sending nodes, A signal environment, and β the path-loss exponent ($2 \leq \beta \leq 6$). Then in our worst case to calculate the inter-cell interference H_{ij} between cells i and j:

$$H_{ij} = \mathscr{F}(c_i, c_j)\, \mathscr{P}(d_{ij}), \tag{3.8}$$

where c_i and c_j are POCs assigned to AP$_i$ and AP$_j$, respectively; $\mathscr{F}(c_i, c_j)$ the channel interference between two cells. For two cells with the same channel $c_i = c_j$, $\mathscr{F}(c_i, c_j) = 1$. Conversely, for two cells with the orthogonal channels, their channel interference $\mathscr{F}(c_i, c_j) = 0$. And with two channels partially overlapped in frequencies, their channel interference $0 < \mathscr{F}(c_i, c_j) < 1$. d_{ij} is the distance between two APs as defined in Section 2.3.1. While Based on these basic models, our objective is to find a policy $\{c_i\}$ of POC assignment:

$$\{c_i\} = \arg_{\{c_i\}} \min \left(\sum_{j:\mathrm{AP}_j \in \Psi} H_{ij} \right) \tag{3.9}$$

Then we can provide the optimization model for the first step based on relaxing from S-CF to R-CF:

$$\min \sum_{i,j:\mathrm{AP}_i,\mathrm{AP}_j \in \Psi, i \neq j} H_{ij} \tag{3.10}$$

s.t.

$$H_{ij} = \mathscr{F}\left(f^i, f^j\right) \mathscr{P}(d_{ij}), \tag{3.11}$$

$$\mathscr{F}\left(f^i, f^j\right) = \begin{cases} 1 - \frac{\left|f^i - f^j\right|}{B}, & \left|f^i - f^j\right| < B \\ 0, & \text{otherwise} \end{cases}, \tag{3.12}$$

$$f_c^1 \leq f^i, f^j \leq f_c^M, \tag{3.13}$$

where f^i refers to the selection of relaxed channel center frequency for AP_i. Formulation (3.10) is the objective to minimize the cumulative network interference; Equation (3.11) is the interference received by AP_i from AP_j; Equation (3.12) is our defined interference model for POCs. In this interference model, we assign channel center frequency R-CF f^i as the relaxed constraint (3.13) to AP$_i$; f_c^1 is the standard center frequency of the first channel; and f_c^M is the responding standard center frequency of the last channel. In this model, we reduce the problem hardness by exploring features of POCs, and converting the integer assignment of channel index to selection of a continuous value.

We assign R-CF to APs to maximize the aggregate downlink capacity without consideration of other aspects. For example, it may result in some unfairness among different cells, with high network capacity for some communication cells while, in contrast, low network capacity for others. This problem usually can be solved by adding fair constraints into the model. Since the hardness to solve the model stems from the piecewise function $\mathscr{F}\left(f^i, f^j\right)$, the details for the solution are as follows by introducing the binary variable y_{ij}^{h}:

$$\min \sum_{i,j:\mathrm{AP}_i,\mathrm{AP}_j\in\Psi,i\neq j} \mathscr{F}\left(f^i,f^j\right)\mathscr{P}(d_{ij}) \tag{3.14}$$

s.t.

$$0\leq f^i-f^j+W*y_{ij}^{1}, \tag{3.15}$$

$$0\leq B-\left(f^i-f^j\right)+W*y_{ij}^{1}, \tag{3.16}$$

$$0\leq \mathscr{F}\left(f^i,f^j\right)-\left(1-\frac{f^i-f^j}{B}\right)+W*y_{ij}^{1}, \tag{3.17}$$

$$0\leq f^i-f^j+B+W*y_{ij}^{2}, \tag{3.18}$$

$$0\leq -\left(f^i-f^j\right)+W*y_{ij}^{2}, \tag{3.19}$$

$$0\leq \mathscr{F}\left(f^i,f^j\right)-\left(1+\frac{f^i-f^j}{B}\right)+W*y_{ij}^{2}, \tag{3.20}$$

$$0\leq f^i-f^j-B+W*y_{ij}^{3}, \tag{3.21}$$

$$0\leq \mathscr{F}\left(f^i,f^j\right)+W*y_{ij}^{3}, \tag{3.22}$$

$$0\leq -B-\left(f^i-f^j\right)+W*y_{ij}^{4}, \tag{3.23}$$

$$0\leq \mathscr{F}\left(f^i,f^j\right)+W*y_{ij}^{4}, \tag{3.24}$$

$$y_{ij}^{1}+y_{ij}^{2}+y_{ij}^{3}+y_{ij}^{4}=3, \tag{3.25}$$

$$y_{ij}^{h}=\{0,1\},h=\{1,2,3,4\}, \tag{3.26}$$

$$f_c^1\leq f^i,f^j\leq f_c^M, \tag{3.27}$$

where W is a constant, which value should be large enough. In this model, optimization variables include relaxed selection of channel center frequency f^i, the interference degree between AP$_i$ and AP$_j$ $\mathscr{F}\left(f^i, f^j\right)$, and binary variables y_{ij}^h for AP$_i$ and AP$_j$ to describe four cases in the piecewise function. Equation (3.14) is the cumulative interference according to (3.8); Inequations from (3.15) to (3.17) as the case 1 are to describe $\mathscr{F}\left(f^i, f^j\right) = 1 - \left(f^i - f^j\right)/B$ for $0 \leq f^i - f^j < B$; Inequations from (3.18) to (3.20) as the case 2 are to describe $\mathscr{F}\left(f^i, f^j\right) = 1 + \left(f^i - f^j\right)/B$ for $-B \leq f^i - f^j < 0$; Inquations (3.21, 3.22) as the case 3 are to describe $\mathscr{F}\left(f^i, f^j\right) = 0$ for $B \leq f^i - f^j$; And Inequations (3.23, 3.24) as the case 4 are to describe $\mathscr{F}\left(f^i, f^j\right) = 0$ for $f^i - f^j < -B$; Equation (3.25) is the constraint on the introduced variables. The piecewise function can be separated into four cases and only one case holds $\left(\text{that is } y_{ij}^k = 0 \text{ for the case } k\right)$ given an instance of $\left(f^i, f^j\right)$, which is described in equation (3.26).

The result in this step is the selection of relaxed channel center frequency. Probably, there are no corresponding channels for the relaxed channel center frequency given an instance of POC configure. In Step 2, we place the constraint to convert S-CF to R-CF. Here, we use a simple approach that selects the nearest S-CF for the given R-CF. Denote the selection result in the first step by $f_{rel} = \left\{f_{rel}^i : \text{AP}_i \in \Psi\right\}$. Since it holds that $\exists k$ such that $f_s^k \leq f_{rel}^i \leq f_s^{k+1}$ the simplest approach is to assign S-CF $f_s^{x_i}$ for AP$_i$ from $\left\{f_s^k, f_s^{k+1}\right\}$ with the smallest separation of channel center frequency (if $k+1 > M$, $x_i = k$):

$$x_i = \arg_k \min \left\{ \left| f_{rel}^i - f_s^k \right|, \left| f_{rel}^i - f_s^{k+1} \right| \right\} \tag{3.28}$$

Let $c_{pro} = \left\{ f_s^{x_i} : \mathrm{AP}_i \in \boldsymbol{\Psi} \right\}$ be the result of POC assignment in the proposal, $c_{opt} = \{c_i : \mathrm{AP}_i \in \boldsymbol{\Psi}\}$ the optimal POC assignment, which is usually a NP-C problem. It probably results in the deviation of network capacity $\boldsymbol{D_c}$ from the viewpoint of SINR (signal to interference plus noise ratio) between our proposal and the optimal result:

$$\begin{aligned} D_c &\triangleq \left| c_{opt} - c_{pro} \right| \\ &= \sum_{i:\mathrm{AP}_i \in \Psi} \left| B \log \left(1 + \frac{P_r}{\sum_{j:j \neq i, \mathrm{AP}_j \in \Psi} \mathscr{F}\left(c_i, c_j\right) \mathscr{P}(d_{ij}) + P_0} \right) \right. \\ &\qquad \left. - B \log \left(1 + \frac{P_r}{\sum_{j:j \neq i, \mathrm{AP}_j \in \Psi} \mathscr{F}\left(x_i, x_j\right) \mathscr{P}(d_{ij}) + P_0} \right) \right|, \end{aligned} \tag{3.29}$$

where P_r is the received power, and P_0 the ambient noise. It can easily find from (3.29) that the deviation of network capacity is depended not only the channel assignment, but also radio configurations including transmitting power, signal propagation A in (3.7), ambient noise P_0 and so forth. To avoid the impact of these parameters on the deviation of network capacity, we define the deviation of the proposal from the optimal result by:

$$\text{dev} \triangleq \left|c_{opt} - c_{pro}\right| = \sum_{i:\text{AP}_i \in \Psi} |f_s^{c_i} - f_s^{x_i}| \tag{3.30}$$

where $f_s^{c_i}$ is the corresponding S-CF for AP$_i$ in the optimal channel assignment. This deviation can be explained as the summation of difference of channel center frequency between the proposed result and the optimal channel assignment for APs. The worst case of deviation occurs seldom when the selection of R-CF for each AP is at the middle of $\left\{f_s^k, f_s^{k+1}\right\}$that is $f_{rel}^{x_i} = \left(f_s^k + f_s^{k+1}\right)/2$, and $\text{dev} = f(l)B/2$ ($f(l)$ is the number of APs in the deployed area, l the number of levels of APs in the deterministic model). Furthermore, the deviation in our proposal can be used as the upper bound to compare with other assignment schemes.

3.4 Evaluation

3.4.1 Parameter Settings

Parameter	**Value**
Solver tool	Lingo [71]
Transmitting power	15dbm
Ambient noise power P_0	-100dbm
Signal propagation A	1
Path loss exponent β	3
Communication range (for 11Mbps)	270 meters
Channel bandwidth B	27.67MHz
Number of orthogonal channels K	3
Number of POCs M	11
Total frequency span T_o	56MHz (2400, 2484)

Table 3.1: Parameter Settings (copyright © 2014IEEE)

We give numerical results to evaluate our scheme for POC assignment in this section. All parameter settings used in the optimization model are summarized in Table 3.1. We use Lingo to solve the optimization model in the first step in our model. The communication range for 11Mbps is about 270 meters. We use a common instance of POC configuration in 802.11b/g with $B = 27.67$MHz, $M = 11, K = 3$ (channels 1, 6, 11), and $T_0 = 56$MHz.

We also evaluate our proposal in the regular string deployment, in which APs are uniformly deployed along the string area.

3.4.2 Numerical Results and Discussion

First, we consider the numerical result in the simple string deployment. To compare with the optimal POC assignment, we give the result for fewer APs in which the optimal POC assignment can be obtained by brute force in order to calculate dev. The result is shown in Table 3.2. In Step 1, we calculate R-CF for APs in the second column. Then, by means of the simplest approach in Step 2, S-CF can be obtained in the third column. For the string deployment as a special case, only the orthogonal channels (channels 1, 6, and 11) among POCs are used. We can also observe from the table that our approach can be used as the optimal scheme in the string deployment since dev $= \mathbf{0}$ in column 4. We give the explanation in Remark 1 in Section 4.

#APs	**Calculate** $\{f^i\}$	**POC Assignment**	dev
3	2413.8, 2441.8, 2469.8	1, 6, 11	0
4	2414.5, 2442.1, 2469.8, 2413.8	1, 6, 11, 1	0
5	2442.1, 2469.8, 2413.8, 2441.5, 2469.2	6, 11, 1, 6, 11	0
...	...	...	...

Table 3.2: POC Assignment in String Deployment (copyright © 2014IEEE)

Fig. 3.2 reports the network capacity for the hexagonal deployment. We normalize the network capacity to $\mathscr{C}(l)/\mathscr{C}_0$, where $\mathscr{C}(l)$ is the network capacity with l levels of APs in the deterministic approach , $\mathscr{C}_o$ the network capacity without interference from other cells. It shows that the normalized capacity in the result of relaxed situation always weighs up the others, which is consistent with our analysis. The final result of POC assignment in the proposal is close to the optimal one, and both are less than that in the relaxed result in Step 1. The difference between the proposal and the relaxed result can be viewed as the deviation of the network capacity, which is also less than the upper bound deviation according to our analysis.

The results above just take into consideration SINR based network downlink capacity in the worst case from prospective of the signal power. However, IEEE 802.11b/g networks are partially depended on used protocols,

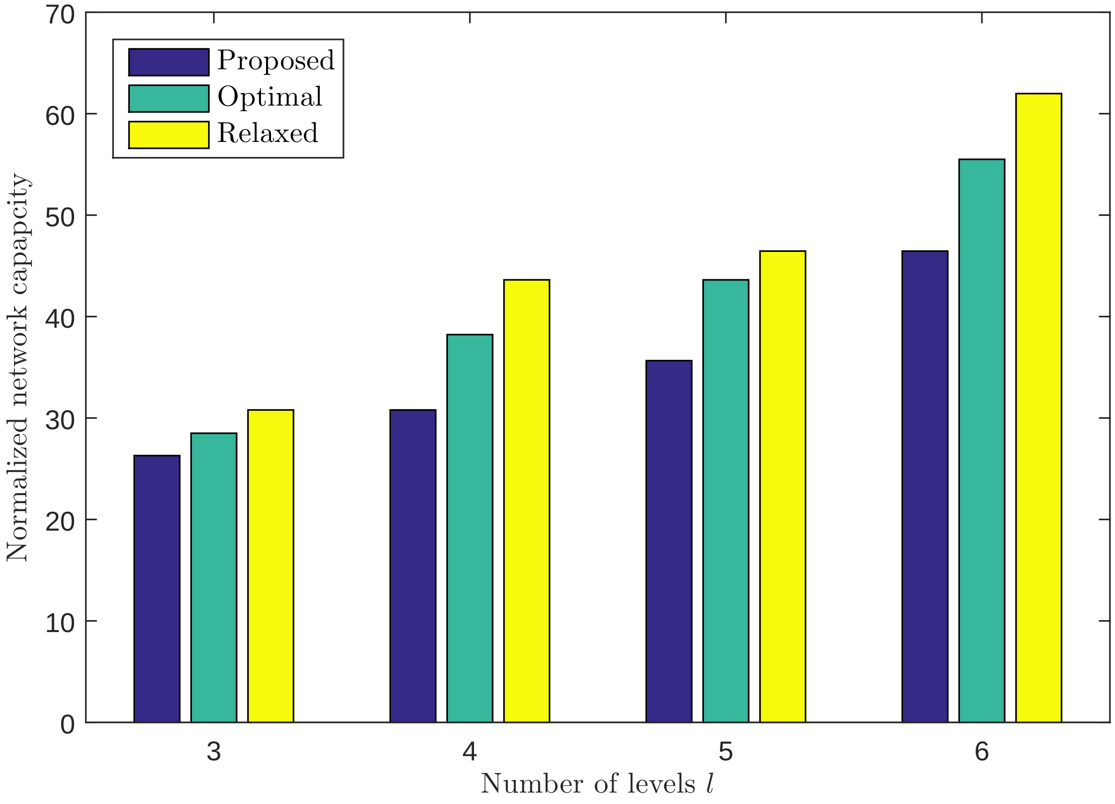


Figure 3.2: Evaluation for hexagonal deployment

CSMA/CA based MAC protocols as an example. Specifically, according to Bianchi's model [7], fewer users in the interference range lead to too much idle time, while more backlogged users lead to too much collision overhead. These works weaken the findings of POC assignment and density recommendation of APs in Section 4.

One reason is that we attempt to find solutions based on the worst case in the assumption. In addition, to answer these questions, the SINR based network downlink capacity fundamentally limits the performance of other aspects. For example, to decode received signals, such as RTS/CTS correctly, the value of SINR must be greater than the given threshold. Also, the transmitting speed relies on the received signal strength. These examples valid the importance of the worst case to calculate inter-cell interference and the scheme of POC assignment to improve network performance in access tier.

3.5 Summary

This chapter deals with the problem of assigning POCs to APs in wireless mesh networks. The key challenges associated with POC assignment problem are mathematical description of POCs and complexity of current methods. We presents a novel approach for POC assignment, and the motivation of this approach is to select channel center frequency for each AP. Based on this approach, we also present an optimization model given the proposed POC model, which reduces the hardness of the POC assignment.

Chapter 4

Joint Design for Deployment Strategies

4.1 Introduction

A deployment solution for these WMNs includes network planning (e.g., placement of mesh routers, number of radios for each router), network integration (e.g., integration of 3G, and LTE technologies), and protocol selection in MAC layer, routing layer and so forth. Two fundamental issues are density of APs and channel assignment since they limit the performance of other aspects. APs should be deployed such that the desired performance, such as network capacity, traffic delay, and etc., is optimized. However, as APs use limited number of channels sharing the same wireless frequency span, AP density should be carefully decided to optimize the network performance by considering inter-cell interference.

We now present the joint design for deployment strategies of density of APs and POC assignment. WMNs are comprised of wireless APs (or mesh routers) that provide users with wireless access service. In this chapter, we study the density of APs with the proposed scheme of POC assignment in the previous chapter. As the overview of the proposal in Fig. 2.3 in Chapter 2, we give an analysis of feasible region, consisting of lower bound and upper bound of density of APs, in which the optimal density lies. Based on this conclusion, we also present a simple algorithm for deployment recommendation of AP density and POC assignment.

4.2 Theoretical Framework

To give the deployment recommendation of AP density and POC assignment, we follow the assumptions in Chapter 3. Two primary assumptions are highlighted here. We use our defined deterministic approach, in which AP density is presented by number of levels l, and the inter-cell interference among downlinks in different cells occurs in the worst case. Thus, given AP density and POC assignment, we can easily calculate exactly inter-cell interference among cells.

Our goal is to provide the maximal aggregate downlink capacity in the area. Due to limited number of channels, the inter-cell interference occurs. Given AP levels l, the cumulative interference for a cell is:

$$I_i = \sum_{j:\mathrm{AP}_j \in \Psi_l / \mathrm{AP}_i} H_{ij}, \tag{4.1}$$

where Ψ_l is the AP set given AP levels l, H_{ij} the inter-cell interference between cell i and cell j in Equation (3.8). The signal-to-interference-plus-noise ratio (SINR) for the downlink in a cell according to the deterministic approach is:

$$\mathrm{SINR}_i = \frac{P_r}{P_0 + I_i}, \tag{4.2}$$

where P_0 is the ambient noise power, P_r the received power. In our analysis, assume $I_i \gg P_0$. The impact of noise is non-negligible, but certainly much smaller than inter-cell interference. Using the Shannon capacity formula, the achievable aggregate downlink capacity of APs is:

$$\begin{aligned}\mathscr{C}(l) &= B \sum_{i:\mathrm{AP}_i \in \Psi_l} \log\left(1+\mathrm{SINR}_i\right) \\ &= B \sum_{i:\mathrm{AP}_i \in \Psi_l} \log\left(1+\frac{P_r}{I_i}\right). \end{aligned} \tag{4.3}$$

To provide the maximal access service into the deployment area, the optimal number of APs is:

$$l_{opt} = \arg\max_{l} \mathscr{C}(l). \tag{4.4}$$

From the discussion above, the desired solution for the optimal number of AP levels is depended on features of POCs and number of AP levels. Unlike orthogonal channel assignment [72], in which there is a assignment pattern independent of deployment area size, the optimal pattern of POC assignment cannot be found. In our analysis, we show that $l_{opt} \in [l_{low}, l_{up}]$ as depicted in Fig. 2.3. The lower bound density of APs l_{low} can be easily found with the constraint of coverage for the interference range according to the used protocols, for decoding RTC/CTS signals correctly, as an example. The main work is to find the upper bound of AP density l_{up}. The significance of upper bound of APs is that it points to an interesting trend that the aggregate downlink capacity decreases if the density is greater than the upper bound. This result provides some useful insights into the deployment strategies. Scaling the network size by deploying more APs than upper bound would be harmful to the network downlink capacity even though giving the optimal POC assignment.

In order to obtain the upper bound density of APs l_{up}, we denote by AP utilization:

$$\mu\left(l+1\right)=\frac{\mathscr{C}\left(l+1\right)-\mathscr{C}\left(l\right)}{6\left(l+1\right)\mathscr{C}_0}, \tag{4.5}$$

where $\mathscr{C}_0$ the normalized AP capacity without interference given channel bandwidth α. It is transparent that $\mathscr{C}\left(l+1\right)-\mathscr{C}\left(l\right)$ is the increment of network capacity by deploying additional $(l+1)$-th level of APs. It permits that the network downlink capacity decreases for deploying $(l+1)$-th level of APs if $\mu\left(l+1\right)<0$. In this chapter, we derive that $\exists l_{up}$ such that $\mu\left(l+1\right)<0$ for $l \geq l_{up}$. The theoretical framework for analysis of the upper bound is organized as follows:

1. We attempt to obtain the upper bound of network capacity $\mathscr{C}_U\left(l\right)$ under proposed Virtual POC Assignment (V-PA), in which $\mathscr{C}_U\left(l\right)>\mathscr{C}\left(l\right)$ for any scheme of POC assignment with network capacity $\mathscr{C}\left(l\right)$. We show that V-PA actually stems from POC assignment for APs in

a line, but not valid in the hexagonal deployment.

2. According to features of POCs, we obtain the lower bound of network capacity $\mathscr{C}_L(l)$, such that $\mathscr{C}_L(l) < \mathscr{C}(l)$ for the optimal POC assignment with network capacity $\mathscr{C}(l)$.

3. Based on the results above, we derive the expression $\phi(l+1)$ that performs as follows:

$$\phi(l+1) > \frac{\mathscr{C}_U(l+1) - \mathscr{C}_L(l)}{6(l+1)\mathscr{C}_0} > \mu(l+1), \tag{4.6}$$

   and $\exists l_\phi$ such that $\phi(l+1)$ decreases with l and converges to 0 for $l \geq l_\phi$. Thus, we can conclude the existence of the upper bound of AP density l_{up}.

In addition, the network capacity increases slowly if $\mu(l+1)$ approximates 0 conditioning on $\mu(l+1) > 0$. Since AP utilization $\mu(l)$ represents the capacity increment by deploying additional level of APs, it will be a waster of resource for low value of AP utilization. To utilize APs with better benefit in capacity , we also introduce another parameter $\mathbf{\Phi}$, which is called the threshold of AP utilization. Thus, to make full use of APs, AP utilization should be greater than the given $\mathbf{\Phi}$.

4.3 Algorithm: Joint Design for Deployment Strategies

According to the theoretical analysis framework of feasible region of AP density, the optimal density of APs can be obtained in the following algorithm, which searches for the optimal number of levels and corresponding POC assignment to maximize the network capacity in the feasible region using the proposed scheme of POC assignment in Chapter 3.

The first input of the algorithm is interference radius r. The value of parameter r is traditionally determined by SINR, that is interfering among cells occurs if SINR for the received signal is greater than the threshold, and otherwise, the received signal is viewed as environment noise. As the assumption in Section 2.3.1, the approach can be extent for the whole physical deployment area by tuning the sensing range larger. Other inputs include our POC configuration (B, Δ_f, K, M) in Section 3.3.2, radio environment parameter β and signal propagation A in Formulation (3.7), and the threshold of AP utilization Φ. Initially, we calculate the feasible region $[l_{low}, l_{up}]$ in Step 1 on the basis of analysis in Section 4.4. In our design, the lower bound of AP density, l_{low} , is obtained conditioning on the simple constraint of covering the interference range. Mainly, we restrict ourselves to the upper

Algorithm 4.1 Joint design of AP density and POC assignment (copyright © 2015IEEE)

```
Input: Interference radius $r$, POC configuration $(B,\Delta_f,K,M)$, radio environment parameter $\beta$, signal propagation $A$, and the threshold of AP utilization $\Phi$
Find the feasible region of the AP density: $[l_{low}, l_{up}]$ according to the approach in section 4.4 ;
Initialize number of levels: $l = l_{low}$, $\mathscr{C}_{max} = 0$, policy of POC assignment $\Xi = \emptyset$;
while $l < l_{up}$ do
    Solve the problem of selecting channel center frequency using the scheme of POC assignment, and the result is $\xi(l)$;
    if $\mathscr{C}_{max} \leq \mathscr{C}_l$ then
        $\mathscr{C}_{max} = \mathscr{C}_l$, optimal number of levels $l_{opt} = l$, POC assignment $\Xi = \xi(l)$;
    end if
    $l = l + 1$;
end while
Output: $l_{opt}$ and $\Xi$.
```

bound of AP density, l_{up}, in the following Section 4.4. In the next step, we initialize the number of levels to the lower bound of AP density and assume that the current network capacity is minimal in Step 2. From Step 3 to 9 in while loop, it simply searches for the optimal density of APs in the feasible region while allocating POC assignment. Finally, the algorithm outputs the optimal number of AP levels l_{opt} and corresponding POC assignment Ξ.

As was discussed in Section 3.3.2, the deviation of proposed POC assignment from the optimal assignment occurs due to the hardness of the problem. We did not consider the deviation while determining the optimal levels of APs in this algorithm by viewing the POC assignment as a module.

4.4 Feasible Region of AP Density

In this section, we provide detailed analysis in line with the theoretical framework for the feasible region of AP density. The objective of this section is to address the challenging issue of determining the upper bound of AP density.

4.4.1 Upper Bound of Network Capacity

To find the desired result, we first give the following remark for APs uniformly deployed along the string.

Remark 1. Only orthogonal channels among POCs are used in the optimal POC assignment for the string deployment.

It is interesting to note that for the simple string deployment where APs are deployed uniformly in a line, the optimal channel allocation is just to use the orthogonal channels among POCs, and the distance between two APs with the same channel is K levels away (by definition of distance between two APs in Section 2.3.1) in accordance with the result in Table 3.2. Intuitively, it can be explained by Equation (3.8): the interference of the user in cell i from cell j is the product of two factors,

$$H_{ij} \propto \mathscr{F}(c_i, c_j)\, d_{ij}^{-\beta},\ 2 \le \beta \le 6.$$

Since the term of channel interference $\mathscr{F}(c_i, c_j)$ can be approximately fitted as a linear function for the interfering channels, and the other term $d_{ij}^{-\beta}$ is a power function of distance d_{ij} (distance between neighboring APs is of the order of $10-100$ meters for high density of APs), the interference from other APs in a line drops more quickly for orthogonal channel than

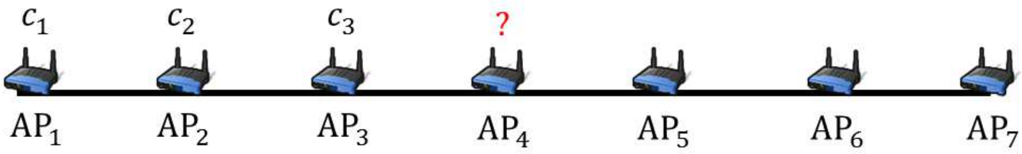


Figure 4.1: Example of POC assignment in the string deployment: How to select a channel for AP_4 given POC assignment for preceding APs? (copyright © 2014IEEE)

channels partially overlapped. For example, in the string deployment one of the optimal channel assignment patterns is **1**, **6**, **11** as shown in the Table 3.2 for $K = 3$ in the IEEE 802.11 b/g. We use an example in Fig. 4.1 to give a visual picture for the remark. Suppose that several APs are uniformly deployed along a line. Given the POC assignment for AP_1, AP_2 and AP_3 according to some scheme of POC assignment, the question is how the channel should be allocated to AP_4 to minimize the interference among these four APs in our deterministic approach? The answer to the problem lies in the feature of POCs. On the one hand, if c_4 is orthogonal with c_2 but overlapping with c_3 , interference increases linearly on the basis of interference model among POCs. On the other hand, if c_4 is overlapping with c_2 but orthogonal with c_3, interference increases exponentially. Thus, c_4 should be orthogonal with c_3.

On the basis of the remark it can minimize the cumulative interference in the network if there is a scheme of POC assignment, which is called Virtual POC assignment (V-PA), in which the orthogonal channels among POCs are just used and the distance between two APs with the same channel is K levels away for each AP. By assuming the existence of V-PA in the hexagonal deployment, the aggregate downlink capacity is maximized if there is only co-channel interference from APs that are K, $2K$, ..., $\lfloor l/K \rfloor K$ levels away. The interference for each AP is:

$$\begin{aligned}\mathscr{I}_V(K,l) &= 6K \sum_{m=1}^{\lfloor l/K \rfloor} m \mathscr{P}(2mKR - R) \\ &= 6KA \sum_{m=1}^{\lfloor l/K \rfloor} m (2mK-1)^{-\beta} R^{-\beta}, \end{aligned} \tag{4.7}$$

where $\mathscr{P}(*)$ is the model for signal propagation in Equation (3.7). Note that in Equation (4.7) the number of interfering APs that are m levels away is $6m$, as an example for the AP at the center in Fig. 2.2 the number of interfering APs in green that are 2 levels away is 12. Now, we can draw the following conclusion in Lemma 2.

Lemma 2. *Given the number of levels of APs l in the deterministic approach, the network downlink capacity cannot exceed the upper bound of network capacity $\mathscr{C}_U(l)$ in conjunction with the scheme of Virtual POC as-*

signment:

$$\mathscr{C}(l) < \mathscr{C}_U(l), \tag{4.8}$$

where

$$\mathscr{C}_U(l) = Bf(l)\log\left(1 + \frac{P_r}{\mathscr{I}_V(K,l)}\right), \tag{4.9}$$

and B *is the channel bandwidth,* $f(l)$*the number of APs, and* P_r *the received power as in signal propagation (3.7).*

Note that V-PA is valid only in the string deployment. In contrast, it does not hold in hexagonal deployment, which produces the situation of being less than the upper bound of network capacity in Formulation (4.8).

4.4.2 Lower Bound of Network Capacity

To derive the lower bound of the aggregate downlink capacity, we first explore network features in the following lemma.

Lemma 3. *Given the number of levels of APs* l *in the deterministic approach, the aggregate downlink capacity for any given POC assignment holds :*

$$\mathscr{C}(l) \geq Bf(l)\log\left(1 + \frac{P_r}{\mathscr{S}(l)}f(l)\right), \tag{4.10}$$

where $\mathscr{S}(l)$ is the cumulative network interference for the given POC assignment:

$$\mathscr{S}(l) = \sum_{i:AP_i \in \Psi_l} \boldsymbol{I}_i, \tag{4.11}$$

and $\boldsymbol{I}_i$ is the interference of AP_i from other APs as defined in Equation (4.1).

Proof. The aggregate network downlink capacity is:

$$\mathscr{C}(l) = \sum_{i:\mathrm{AP}_i \in \Psi_l} \mathscr{C}_i = \sum_{i:\mathrm{AP}_i \in \Psi_l} \log\left(1 + \frac{P_r}{\boldsymbol{I}_i}\right), \tag{4.12}$$

where $\mathscr{C}_i$ is the downlink capacity for AP_i. Recall that $\mathscr{C}_i$ is a convex function of $\boldsymbol{I}_i$, and there are $\mathrm{f}(l)$ APs in AP set Ψ_l, which implies the following inequality:

$$\frac{B}{\mathrm{f}(l)} \sum_{i:\mathrm{AP}_i \in \Psi_l} \log\left(1 + \frac{P_r}{\boldsymbol{I}_i}\right) \geq B \log\left(1 + \frac{P_r}{\sum_{i:\mathrm{AP}_i \in \Psi_l} \boldsymbol{I}_i / \mathrm{f}(l)}\right). \tag{4.13}$$

By means of Equations (4.11) and (4.12), it can derive:

$$\frac{1}{\mathrm{f}(l)} \mathscr{C}(l) \geq B \log\left(1 + \frac{P_r}{\mathscr{S}(l)} \mathrm{f}(l)\right). \tag{4.14}$$

Hence, we complete the proof. □

By means of Lemma 3 the lower bound of network capacity can be derived if giving the cumulative network interference for the optimal POC assignment, which is denoted by $\mathscr{S}_{opt}(K,l)$. It is intuitively to say that the cumulative interference for the optimal POC assignment is not greater than the cumulative interference, which is denoted by $\mathscr{S}_{ort}(K,l)$ for using only orthogonal channels of K types among POCs since they are included in M POCs. Therefore, the network capacity for the orthogonal channel assignment can be viewed as the lower bound of network capacity $\mathscr{C}_L(l)$.

While only orthogonal channels of K types among POCs are used in the network, AP density for each orthogonal channel type is:

$$\rho = \frac{\mathrm{f}(l)}{K} \tag{4.15}$$

since orthogonal channels of K types are uniformly assigned to APs [72]. The separation between co-channel APs is:

$$D = \frac{2r}{\sqrt{\rho}}. \tag{4.16}$$

Note that for orthogonal channel assignment [72], the number of levels for the co-channel interference is $\lfloor r/D \rfloor$, while the number of interfering APs co-channel interference from m levels away is $6m$. Meanwhile, the interference distance at the worst case as defined in our deterministic approach for two cells m levels away is $(mD-R)$. Using Equation (4.16), the cumulative interference $\mathscr{S}_{ort}(K,l)$ in orthogonal channel assignment is:

$$\begin{aligned}\mathscr{S}_{ort}(K,l) &= 6\mathrm{f}(l)\sum_{m=1}^{\lfloor r/D \rfloor} m\mathscr{P}(mD-R) \\ &= 6A\mathrm{f}(l)\sum_{m=1}^{\lfloor r/D \rfloor} m\left(2m\sqrt{K}-1\right)^{-\beta} R^{-\beta}. \end{aligned} \tag{4.17}$$

On the basis of Lemma 3, the lower bound of network capacity $\mathscr{C}_L(l)$ is:

$$\begin{aligned}\mathscr{C}_L(l) &= B\mathrm{f}(l)\log\left(1+\frac{P_r}{\mathscr{S}_{ort}(K,l)}\mathrm{f}(l)\right) \\ &= B\mathrm{f}(l)\log\left(1+\frac{P_r}{6A\sum_{m=1}^{\lfloor r/D \rfloor} m\left(2m\sqrt{K}-1\right)^{-\beta} R^{-\beta}}\right). \end{aligned} \tag{4.18}$$

4.4.3 Upper Bound of AP Levels

In this section, we further study the upper bound of AP levels based on the conclusions in the preceding sections. According to Lemma 2, it can say that for the optimal POC assignment with network capacity $\mathscr{C}(l)$: $\mathscr{C}(l) < \mathscr{C}_U(l)$.

We can also see that $\mathscr{C}(l) > \mathscr{C}_L(l)$ from Lemma 3.Then, we can find that:

$$\frac{\mathscr{C}(l+1) - \mathscr{C}(l)}{6(l+1)\mathscr{C}_0} < \frac{\mathscr{C}_U(l+1) - \mathscr{C}_L(l)}{6(l+1)\mathscr{C}_0}. \tag{4.19}$$

By means of Equations (4.9) and (4.18), we have:

$$\begin{aligned} &\frac{\mathscr{C}_U(l+1) - \mathscr{C}_L(l)}{6(l+1)\mathscr{C}_0} \\ &< \frac{B\mathrm{f}(l+1)\log\left(1+\frac{P_r}{\mathscr{I}_V(K,l+1)}\right) - B\mathrm{f}(l)\log\left(1+\frac{P_r}{6A\sum_{m=1}^{\lfloor r/D\rfloor} m\left(2m\sqrt{K}-1\right)^{-\beta} R^{-\beta}}\right)}{6(l+1)\mathscr{C}_0} \end{aligned} \tag{4.20}$$

To evaluate the impact of different POC configuration on the performance, here we use the normalized network capacity $\mathscr{C}_0$ without inter-cell interference for the fixed channel bandwidth α:

$$\mathscr{C}_0 = \alpha \log\left(1+\frac{P_r}{P_0}\right). \tag{4.21}$$

We denote the right side of the preceding Equation (4.20) by $\phi(l+1)$ which permits that $\exists l_\phi$ such that $\phi(l+1)$ decreases until converging to 0 for $l \geq l_\phi$. This can be accomplished from the derivative of $\phi(l+1)$, conditioning on the fact that the cumulative interference in the orthogonal channel assignment is mainly from the nearest levels of interfering APs as follows:

$$\begin{aligned}\phi'(l+1) =& \frac{B\left(3l^2+6l+2\right)}{(l+1)}\log\frac{1+\frac{6A}{y_2}}{\left(\mathscr{G}(K)\frac{\mathrm{f}(l+1)}{\mathrm{f}(l)}\right)^{\beta/2}+\frac{6A}{y_2}} \\ &+\frac{3B\beta}{2\mathscr{C}_0}\left(\frac{2l+1}{1+\frac{6A}{y_1}}-\frac{2l+3}{1+\frac{6A}{y_2}}\right),\end{aligned} \tag{4.22}$$

where

$$\begin{aligned}\mathscr{G}(K) &= \left(\frac{2K^{1/2+1/\beta}-K^{1/\beta}}{2K-1}\right)^2, \\ y_1 &= P_r\left(2\sqrt{K}-1\right)^\beta\left(\frac{r}{\sqrt{\mathrm{f}(l)}}\right)^\beta, \\ y_2 &= P_r\frac{(2K-1)^\beta}{K}\left(\frac{r}{\sqrt{\mathrm{f}(l+1)}}\right)^\beta.\end{aligned}$$

In spite of no close-form expression for $l_\phi$in (4.22) due to the complexity of algebraic calculation, we convincingly demonstrate its existence from the following discussion. First recall that:

$$\mathscr{G}(K) \leq \frac{4-\sqrt{2}}{3} \tag{4.23}$$

for $K \geq 2$ and $\beta \geq 2$, and

$$y_1 < y_2 \tag{4.24}$$

for $l > 4$. From relationships in (4.23) and (4.24) it gives rise to:

$$\mathscr{G}(K)\frac{\mathrm{f}(l+1)}{\mathrm{f}(l)} \leq 1. \tag{4.25}$$

Furthermore, The right side of expression (4.22) for $\phi'(l+1)$ is the summation of two factors, in which the first term is great than 0 and converges quickly to 0 with l, whereas the second term is less than 0 and converges to 0 slower than the first. Therefore, $\exists l_\phi$ such that $\phi'(l+1) < 0$ for $l \geq l_\phi$. Referring to (4.19), AP utilization $\mu(l+1)$ in (4.5) is said to be the upper bound of AP utilization for $l \geq l_\phi$. Consequently, we demonstrate the existence of the upper bound of AP levels.

4.5 Numerical Results

In this section, we present the numerical results in our proposal for the deployment recommendation for joint issue of AP density and POC assignment in the hexagonal deployment. We describe the performance from aspects of feasible region and aggregate downlink capacity.

4.5.1 Simulation Settings

We primarily follow simulation settings in Chapter 3, but focus on the impact of different POC configuration on the performance. We use (M, K) to describe POC configuration as presented in Section 3.3.2. Another setting, the threshold of AP utilization Φ as introduced in Section 4.2, is associated with the upper bound of AP density.

4.5.2 Performance Evaluation

The dependence of upper bound of AP density on the AP utilization is shown in Fig. 4.2. The number of levels at the peak in each curve represent corresponding value of l_{ϕ}. It examines the fact that $\exists l_{\phi}$ such that AP utilization decreases for $l \geq l_{\phi}$, which demonstrates the existence of the upper bound of AP density. It also shows that the trend of AP utilization becomes greater while dividing the frequency band into greater number of POCs given a fixed number of orthogonal channels, since the interference among POCs becomes less harmful, and the utilization efficiency of POCs gets higher in the higher density of networks. Roughly speaking, one can expect more benefits of aggregate downlink capacity for narrower bandwidth of each channel given fixed frequency span due to less overlapping

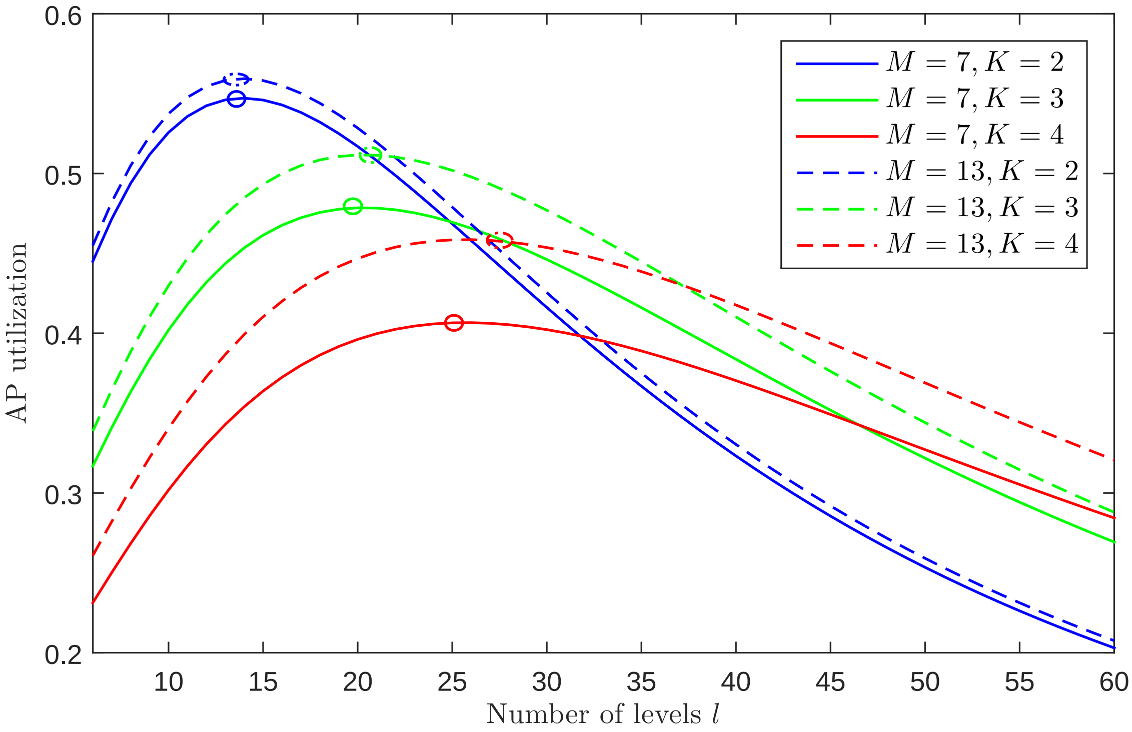


Figure 4.2: Existence of l_ϕ (copyright © 2015IEEE)

frequencies among neighboring cells.

Fig. 4.3 shows the impacts of POC configuration on the network capacity in the hexagonal deployment. We first obtain the aggregate downlink capacity $\mathscr{C}(l)$ using our proposed scheme of POC assignment. We, then, use equivalent number of active levels L to normalize the aggregate downlink capacity $\mathscr{C}(l)$:

$$L = \arg_L \left(\mathscr{C}(l) = \left(3L^2 + 3L + 1\right) \mathscr{C}_0 \right),$$

where $\mathscr{C}_0$ in Equation (4.21) is downlink capacity without inter-cell interference from other cells for $\alpha = 45$MHz. Thus, we can easily visualize the aggregate downlink capacity by means of equivalent number of active levels. A greater equivalent number of active levels permits higher aggregate downlink capacity. In Fig. 4.3, the network capacity for the POC configuration ($M = 7,\ K = 3$) is slightly greater than for the POC configuration ($M = 13,\ K = 4$) for the network with low density of APs ($l = 4$). Since the channel bandwidth is about 30MHz for POC configuration ($M = 7,\ K = 3$) and about 20MHz for POC configuration ($M = 13,\ K = 4$), and the distance between cells is larger, fewer inter-cell interference occurs among cells. Therefore, it gives rise to the higher aggregate downlink capacity for the greater channel bandwidth. Generally, the impact of POC configuration can be very detrimental to the network performance, and POCs can contribute more gains in the high density networks.

From our analysis, we can identify that the upper bound numbers of levels for POC configurations ($M = 7,\ K = 3,\ \Phi = 0.47$) and ($M = 13, K = 4,$ $\Phi = 0.45$) are 23 and 30, respectively. Then, the optimal number s of levels are 16 and 22, respectively, by means of the proposed Algorithm 4.1. To give an imaginable picture of AP deployment, the distance between two APs is about 9 meters for POC configuration ($M = 13,\ K = 4,\ \Phi = 0.45$). We believe that it is reasonable to deploy such high density of APs since there are 4 orthogonal channels among POCs, and the distance for two APs with the same channel is about 35 meters for the same AP density with 22 levels if only 4 orthogonal channels are used. Generally, it can produce greater SINR downlink capacity for more number of POCs by dividing the given frequency span. However, it also cost higher overhead accordingly since it takes more time, such as for associating procedure, channel selection, handover when moving from one cell to another one, and so forth, for a narrower channel band .

The results can be used to recommend deployment strategies of AP density and POC assignment based on our analysis. However, we did not consider impact of other aspects, fairness issue among cells, protocols used, etc. As expected, the algorithm need to consider them if these constraints are introduced into the model with the same analysis process for the feasible region. Another limitation is from our POC configuration based on dividing the given frequency span. In fact, we use fixed frequency band fro each channel. However, our proposal can be in self-defined scenarios, such as WMNs for military battle, disaster area, and so forth.

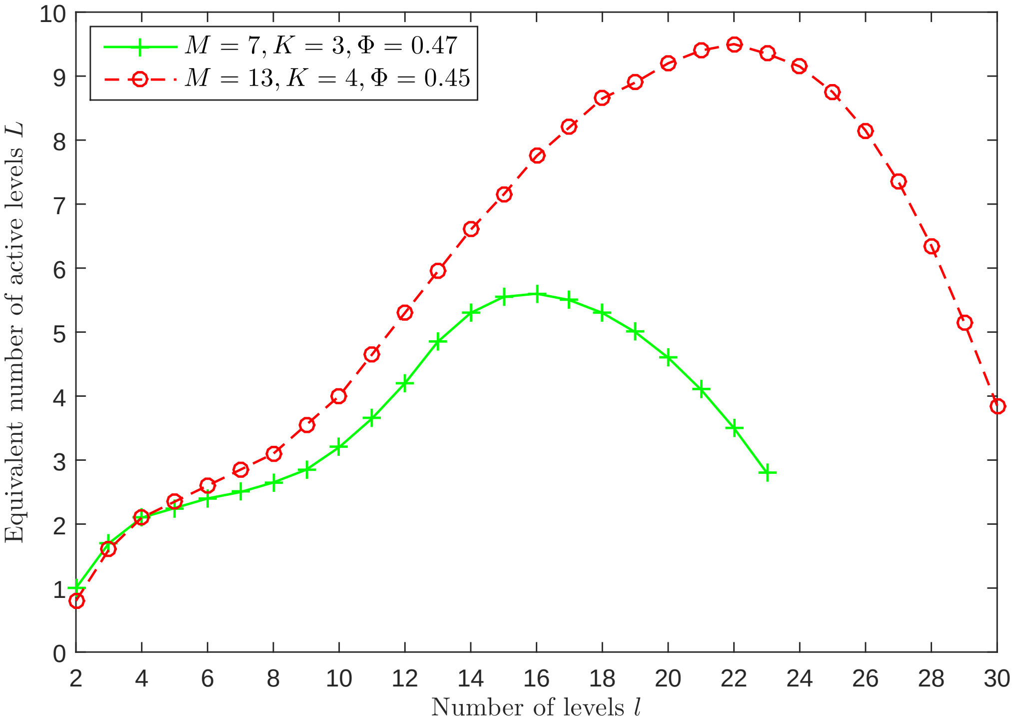


Figure 4.3: Normalized aggregate downlink Capacity (copyright © 2015IEEE)

4.6 Summary

In this chapter, we have studied how to address the joint issue of the density of APs and POC allocation for the maximal aggregate downlink capacity in WMNs. It is intuitive to note that the network capacity can be scaled by providing additional APs in a given area since the expected distance from users to the associated APs becomes shorter. On the other hand, the additional increment of network capacity by means of deploying more APs is limited. It can be accredited to the substantial interference among the high number of deployed APs assigned with POCs. To cope with these challenges, we study the problem of interaction between density of APs and POC assignment, in which we derive that the optimal density of APs lies in the feasible region consisting of the lower bound and upper bound density. Thus, the solution can be obtained by searching for the feasible region by means of the proposed POC assignment. Through analysis and numerical results, we provide recommendations on the optimal dimension of high density and POC assignment for wireless mesh network deployment.

Chapter 5

Conclusions

5.1 Summary and Discussions

In this thesis, we are devoted to the investigation of deployment strategies of access tier in WMNs for high downlink capacity of wireless access provisioning since they are the fundamental issues for the network planning. We showed that existing work is lack of essentials required to recommend deployment strategies. Our contribution is a solution that requires no knowledge of user distribution, which is more practical, and is amenable to real-world deployments. The primary contributions of this dissertation are listed as follows.

- In Chapter 1, we provided a comprehensive introduction to the recent developments of wireless mesh networks (WMNs), and also discussed the opportunities and challenges of wireless mesh networks.

- We started our study by verifying our deterministic methodology and utilization of POCs for high capacity wireless access provisioning in Chapter 2. In addition, literature about deployment methodologies and schemes of POC assignment is also viewed in this chapter. Followed pointed out motivations of our study for the deployment strategies. And considered the deployment strategies of APs from the perspective of regular hexagonal deployments, which can be used in the phase of network planning. Finally, we provided an overview of our deployment recommendation based on the proposed POC assignment.

- In Chapter 3, we generalized POC model including POC distribution and channel interference model, and investigated that POCs can obtain the higher network capacity and better utilization of channels in the spectrum span. To avoid the hardness of POC assignment stemming from the integer index (channel index) assignment, we explored the characterization of POCs and proposed a novel POC assignment from the perspective of channel center frequency. Following this work, we conducted numerical evaluation for the hexagonal deployments and demonstrated the effectiveness of our proposal of POC assignment.

- Based on the general POC model, we derived in Chapter 4 that the network capacity decreases with the AP density when AP density is greater than the upper bound, and the optimal density lies in the feasible region consisting of the lower bound and the upper bound of AP density combining POC assignment. To prove this conclusion, we derived another 2 claims to show the network performance with the context of POCs. Then, we designed a simple algorithm to search for the optimal density within the feasible region. At last, we presented numerical result to validate our design and performance aspects of our solution.
- In Chapter 5, we summed up our thesis and discussed the possible extension of our current work.

5.2 Future Work

In this dissertation, we provided deployment recommendation if joint design for AP density and POC assignment upon which many avenues for future work can be explored.

- Notice that the result of feasible region developed in this dissertation holds currently for our channel interference model: the channel interference between two channels is linear with their channel separation. Even furthermore, it depends on the conclusion that only orthogonal channels among POCs are applied to in string deployment as analyzed in Remark 1, on which the other conclusions in our dissertation rely. Despite that the proposed interference model for POCs characterizes their features, it is still a specific model, based on a piecewise function, to describe their relationship. So one of our future research directions is to find constraints on the POC model to identify the situation where our proposal can be applied.

- We considered the network capacity from the viewpoint of SINR model. Though it fundamentally limits the network performance for the impact of other aspects, protocols in the routing layer [73], DCF [74] in MAC layer, and etc., applied in the concrete scenario have a significant influence on the network performance. Therefore, another extension of our current work is to consider the recommendation of AP density and POC assignment with concrete protocols.

- Nowdays, APs not only operate to provide access service to users, but also can relay traffic from other APs as a router. In this dissertation, we studied the network performance for the downlink only in access tier of WMNs by assuming that there is no limitation on relaying the traffic among APs. Even though there is no channel interference (by means of technologies of OFDM, beamforming, 5G, etc.) for relaying links, the effect of "hotspot" [75], some nodes have a large amount of traffic to relay, may occur. It will result in the result that there is no gains to deploy more APs since the traffic at the "hotspot" exceeds its capacity [76, 77]. Thus, one immediate extension is to incorporate relaying among APs. More specifically, the joint design between access tier and backhaul tier of relaying traffic relies on the specific network architecture. On the one hand, it can easily merge two parts if their channel frequency spans are in different spectrum, such as 2.4GHz and 5GHz. On the other hand, cross layer design has to be considered, otherwise.

- In our results, we gave a conclusion that it brings more gains by dividing the given frequency span into more channels since less inter-cell interference occurs, without consideration of overhead from other operations, such as association [78] to an AP, handover [79] from one cell to another, and so forth. To provide the best service to users for given fixed network deployment, the tradeoff between dividing more channels and costing less overhead will be an extension to our current work.

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Journals

1. Zhao, W.; Nishiyama, H.; Fadlullah, Z.; Kato, N.; Hamaguchi, K., *"DAPA: Capacity Optimization in Wireless Networks through a Combined Design of Density of Access Points and Partially Overlapped Channel Allocation,"* Vehicular Technology, IEEE Transactions on , vol.PP, no.99, pp.1,1 doi: 10.1109/TVT.2015.2437714

Refereed Conference Papers

2. Zhao, Wei, et al. *"Characterizing the impact of non-uniform deployment of APs on network performance under partially overlapped channels."* Wireless Algorithms, Systems, and Applications. Springer Berlin Heidelberg, 2013. 244-254.
3. Zhao, Wei, et al. *"Joint design of density of access points and partially overlapped channel assignment for capacity optimization in wireless networks."* Wireless Communications and Signal Processing (WCSP), 2014 Sixth International Conference on. IEEE, 2014.
4. Wei Zhao; Fadlullah, Z.; Nishiyama, H.; Kato, N.; Hamaguchi, K., *"On joint optimal placement of access points and partially overlapping channel assignment for wireless networks,"* Global Communications Conference (GLOBECOM), 2014 IEEE, pp.4922,4927, 8-12 Dec. 2014

Best Paper Awards

1. Zhao, Wei, et al. *"Characterizing the impact of non-uniform deployment of APs on network performance under partially overlapped channels."* Wireless Algorithms, Systems, and Applications. Springer Berlin Heidelberg, 2013. 244-254.

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