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WiFi 網路規劃之接取點布置與通道指定平台

Access Point Placement and Channel Assignment Platform for WiFi Network Planning

陳仕勳
Shi-Shiun Chen

指導教授：魏宏宇博士

Advisor: Hung-Yu Wei, Ph.D.

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本論文係陳仕勳君 (R01921029) 在國立臺灣大學電機工程學研究所完成之碩士學位論文，於民國 103 年 7 月 15 日承下列考試委員審查通過及口試及格，特此證明

口試委員：

所　長：

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本論文能夠順利完成，首先要感謝我的指導教授魏宏宇在碩士班兩年來提供研究上的指導與協助，也要感謝口試委員謝宏昀教授、逄愛君教授、王志宇博士、林咨銘博士對本研究提供的建議，使這篇論文更加完善。另外也要感謝實驗室的學長姐陳彥賓、周敬淳、趙式隆、林冠宇、施美如在研究過程中與我共同討論與分享經驗，此外還有一同努力的實驗室同屆同學林奕廷、葉哲瑋、吳柏賢、董展羽、廖冠傑在這段期間的互相幫忙與打氣。更要感謝我的家人在我求學過程中精神上與經濟上的支持，以及女友的鼓勵與陪伴，還有心理師柯書林在我大學生活以來提供的諮詢與幫助。最後要感謝我的朋友們，你們的關心是我繼續前行的一大動力。

摘要

無線區域網路的設計是一項複雜的作業，許多觀點包括信號覆蓋率、干擾、流量管理都需要納入考量。在這份研究中我們實作了可以幫助無線區域網路設計的 WiFi 網路規劃平台。這個平台包含三個模組 ——信號強度模組、接取點布置模組、通道指定模組。信號強度模組可以為運作的接取點產生信號強度分布圖，使設計者能評估布署狀況。接取點選擇模組利用最佳化的方法，從一組候選的接取點中選出適當的接取點組合，以提供足夠的信號覆蓋以及達到設計者對網路吞吐量的要求。通道指定模組則分配可用的通道給被選上的接取點，以最小化同通道上的干擾。此平台以程式語言 Matlab 和 C 語言撰寫而成，而在 C 語言的程式庫中也有應用程式介面提供實際應用。

關鍵字*: 802.11*、*WiFi*、網路規劃、最佳化、無線區域網路、接取點

Abstract

The design of a wireless local area network (WLAN) is a complicated work that demands considerations of many aspects including signal coverage, interference, and traffic management. In this paper we implement a WiFi network planning platform that is able to assist the design of WLAN. The platform consists of three modules: the signal strength module, the AP location planning module, and the channel assignment module. First, the signal strength module generates signal strength maps for operating AP(s) so that a designer can evaluate the deployment. Next, the AP selection module uses an optimization technique to choose APs from a candidate AP set, and the selected APs can provide sufficient coverage and satisfy the throughput requirement specified by designer. At last, the channel assignment module allocates available channel to the selected APs and aims to minimize the co-channel interference of them. The platform is written in Matlab and C, and an application programming interface is also implemented in C-based library for practical application.

Keywords: 802.11, WiFi, Network Planning, Optimization, Wireless Local Area Network, WLAN, Access Point, AP

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Chapter 1

Introduction

Wireless local area network (WLAN) based on IEEE 802.11 technology is widely used to provide wireless broadband Internet access for both private and public environments. In private environments, users usually only need single access point (AP) and the deployment is unstructured. However, for public places demands higher traffic a structured deployment of APs that belong to one administrative domain is required. The design of WLAN for such scenario involves many performance factors such as coverage, interference, cost, capacity, and efficiency of resource utilization.

In this paper we implement a WiFi network planning platform for WLAN deployment. The network design problem is divided into two parts as candidate AP selection and channel assignment. We use a better estimation of throughput, and integrate the procedure into the optimization algorithm for the decision of selecting APs. For the selected APs, we also generate a channel allocation plan to minimize the interference caused by APs operating on the same channel.

In addition to the ability to offer an initial plan for network deployment, our platform can also provide plans to already deployed networks for adjusting the operating APs according to the number of served users. We utilize the people density map to make the decision of AP selection, and designers can modify the people density of the target area to produce different AP selection plans for various number of users. The approach is useful for places like museums, exhibition halls, theme parks, and stadiums where the number of visitors changes with time.

The paper is organized as following: We would introduce the related works of our research in Chapter 2. A detailed survey for the propagation model of IEEE 802.11 and cell communication technologies is presented in Chapter 3. We would describe the design specifications and the optimization model of our algorithm in Chapter 4 We would explain the function and detail of our WiFi network planning platform in Chapter 5, and the performance of our platform is evaluated in Chapter 6 Finally, the work of this paper is concluded in Chapter 7.

Chapter 2

Related Work

In the following sections, we will introduce approaches to WiFi network planning and outline several optimization algorithms that have been applied to this problem.

2.1 WiFi Network Deployment Approaches

Wireless network design traditionally involves two types of approaches [1]. The first approach is based on a site survey with intense experimental deployments, measurements, and decisions. In this procedure designers have to evaluate potential positions of APs by visiting the target environment. They may begin with deploying temporary APs at initial locations, and then acquire a whole vision of the signal coverage and quality of service (QoS) conditions via a complete measurement. Finally the designers can determine a set of proper placements and configurations of APs for the target area. The process is usually time-consuming and costly and thus not suitable for large wireless network planning. Also, capacity analysis for such deployment is difficult to handle. The deployment may not have enough capacity for demanded traffic load.

Software planning is the other approach that is faster, more economic, and more flexible than site survey. With software network planning tools, designers can examine the performance of many different deployments with little expenses. However, the simulation output may be not precise without careful design. Whether a software network planning is successful or not depends on the accuracy of the inputs that describe target environment and the propagation model that simulate the signal distribution. Especially, an accurate propagation model can provide user a realistic view of signal coverage resulted by candidate APs, and it is a key component of software planning. Propagation models frequently used in previous works include ray-tracing model, multi-wall model, Dominant Path Model [2, 3] which finds a dominant path and compute its path loss from source to destination point, Motif Model [4] which utilizes a large radiation pattern database for generating signal coverage maps in high speed.

To address the drawbacks of the two approaches, most software vendors combine those two approaches in their product to reduce the number of measurements. Primary environmental information is obtained by site survey module, and it is incorporated in software planning module to develop a more realistic simulation result. The site survey technique is also used to verify a deployment. Examples of such tools include AirMagnet Survey from Fluke Networks [5], Ekahau Site Survey from MetaGeek [6], HiveManager from Aerohive Networks [7], LanPlanner from Motorola [8], RingMaster Software from Juniper Networks [9], and WinProp from AWE Communications [10]. There is also a wireless sensor network design tool called Wi-Design proposed in [11].

In recent years, research about WiFi network design is associated with building automation systems. In [12–14], the network design tool is integrated with building automation systems to construct a framework which is able to manage the wireless network that involve different devices and different technologies.

2.2 Optimization Algorithms for WiFi Network Planning

Generally, the goal of wireless network design is to find a set of AP locations and/or channel allocation plan to achieve maximum performance. The performance metrics of a network design can be judged by several metrics as signal coverage, maximum throughput, goodput, co-channel interference, etc. Many optimization algorithms have been proposed to address wireless network design problem and evaluated by some of the above performance metrics. Recent examples of those algorithms are mathematical optimization approaches such as integer linear programming (ILP) [15] and mixed integer linear programming (MILP) [16, 17], meta-heuristic approaches such as simulated annealing [18], tabu search [19, 20], evolution strategies (ES) [21], genetic algorithms [22], and iterative neighborhood search [23, 24]. Also, a detailed survey about channel assignment and AP placement algorithms is provided in [25].

Mathematical optimization with solution-oriented modeling is one of the popular techniques in solving wireless network design problem. The general concept, the ready-made optimization models, the programming tools, and a basic demonstration is described in [26]. Because there are typically multiple conflicting criteria (e.g., signal coverage vs. cost, throughput vs. interference, etc.) which demand evaluation, an analysis of the solutions on the Pareto front is required [20]. In [27] the problem is modeled by MILP to maximize total throughput and minimize co-channel overlap, and in [17] the MILP model is modified to cover the exposed terminal problem in WiFi network. The mathematical model depicted in [17] is used as a reference of the mathematical formulation in our work.

Although mathematical programming is powerful in finding the optimal solution, some important details in network planning problem is oversimplified to fit the math model. For instance, the throughput calculation in those research is only treated as a mapping from signal strength, and the effect of user competition is ignored. Consequently, the algorithms may overestimate the throughput performance of the resulted deployment and fail to reach designer's requirement. Besides, in some research the mathematical model is too complex to solve by a ready-made tool, instead a heuristic approach is proposed to address such model. For example, in [28] the author formulate the wireless network planning problem into a quadratic set covering problem to maximize capacity and coverage, and later the quadratic function is solved with a heuristic approach in [29]. In short, a greedy method is taken to get an initial solution, then followed by local search algorithms to tune the solution. In addition, in order to reduce the computational complexity of ILP, another research [30] utilizes the Markovian cluster algorithm to divide the overall environment into a number of regions that can apply ILP individually.

The meta-heuristic approaches is another one of the popular techniques in solving wireless network design problem due to the difficulty and complexity of handling mathematical formulations. They are strategies that guide the search process, and the goal is to explore the search space efficiently in order to find near-optimal solutions. For example, in [22] a specified genetic algorithm is proposed to design a realistic wireless network set up in Finland. The genetic algorithm uses a chromosome with six genes (device type, antenna type, transmission power, reuse packing factor, and reuse pattern coordinates X&Y) and a fitness functions include seven metrics (capacity, goodput, capacity fairness of APs, coverage, deployment cost, mean service capacity, and fairness of service). The weighting of the metrics in the fitness function can be adjusted according to designer's preferences. Moreover, in [31] the author solves the design problem of open WiFi access networks with non-dominated sorting genetic algorithm (NSGA) and harmony search (HS). The multiple objectives are deployment cost and percentage of non-covered users, and a performance comparison on the Pareto front is conducted with those two algorithms.

Although those meta-heuristic approaches reduce the time complexity to some extent, they may not ensure the convergence to a near-optimal solution when the problem size increases. A novel algorithm called agent-based algorithm [32,33] was proposed to address the scalability problem. In the research a candidate AP is regarded as a decision-making agent, and it can take actions such as moving, changing channel, or splitting to maximize its utility based on the limited information of itself. The algorithm also make agents collaborate with each other by a cooperative game design. Therefore a large problem can be divided by local views of agents.

The performance of the meta-heuristic approaches outlined above heavily relies on proper weighting in the fitness function. A weighting without tuning on the metrics may lead to poor solution quality. However, how to adjust the weights of different metrics may be a headache to designers because appropriate weighting may differ in different environment setting.

There is another research [34] about small cell deployment that can be applied to the WiFi network planning problem. The authors formulate a joint optimization problem involving deployment location, transmit power, and cell selection to maximize the supported users for the given number of femtocells. The problem is formulated as mixed-integer non-linear programming (MINLP) form, and decoupled into the cluster formation sub-problem and power control sub-problem. In [35], the authors also discuss the extensions of this work as co-channel deployment, post-deployment optimization, and resource block allocation. The algorithm proposed in this work satisfies as many users as possible to meet user's throughput requirements for the given number of femtocells; in contrast, our algorithm minimizes the number of the deployed AP such that the throughput requirements of all users are reached.

The aim of our work is to provide an efficient approach to wireless network design. The algorithm is based on [36], which allows the designer to prioritize the area and then utilize a greedy heuristic in AP selection and channel assignment. Besides, the algorithm only require two optimization parameters which are the defined signal strength difference of the top two AP in the most and least important area. We have modified the algorithm to ensure the throughput of every target location, whereas most of the algorithms only optimize the total capacity of the whole area but do not discuss whether the throughput at each location satisfy the requirement. Also, the effect of user competition is modeled in our work to estimate the throughput in a more realistic way, whereas most of the algorithms only view throughput as a mapping from signal strength to data rate.

A comparison of optimization goals between our algorithm and other algorithms introduced in this section is summarized in Table 2.1. The throughput optimization can be classified to two types: fixed or dynamic. Fixed throughput optimization means that the algorithms of such type regard throughput as a simple relation between signal strength and data rate, while dynamic throughput optimization means that the throughput calculation in those algorithms is not merely a mapping from signal strength. In [19–21, 32, 33] and our work, the throughput calculation involves the consideration of user number. With more user served under an AP, the actual throughput would decrease due to user competition. However, the algorithms used in those papers all divide the target environment into several blocks and only optimize the average throughput in those blocks. The approaches may let the demand at some locations be unsatisfied. Our algorithm examine the throughput of every target location and ensure the requirement is achieved.

Table 2.1: Comparison of Optimization Goals

Paper	Throughput		SNR	Interference	Transmit Power	Cost	Coverage Area
	fixed	dynamic					
Our work		✓					
[15]	✓						
[16, 17, 27]	✓			✓			
[18]			✓		✓		
[19, 20]		✓	✓		✓		
[21, 32, 33]		✓	✓				
[23, 24]			✓				
[29]	✓						✓
[30]				✓			✓
[31]						✓	✓
[36]				✓			✓
[34, 35]		✓		✓	✓		

Chapter 3

Propagation Loss Model Survey

In this chapter, we survey several propagation loss models defined in IEEE 802.11n, IEEE 802.11ac, IEEE 802.11ah, and 3GPP cell communication standards. These models can be utilized in the network planning platform for calculating the signal coverage over the whole area. We have implemented the propagation loss models of IEEE 802.11n, IEEE 802.11ac, and IEEE 802.11ah in the WiFi network planning platform.

3.1 Channel Model Survey of IEEE 802 Standards

3.1.1 IEEE 802.11n & IEEE802.11ac

IEEE802.11n [37] and IEEE802.11ac [38] standards use the same propagation loss model. In TGn and TGac channel models, six channel models are defined for different environments (model A-F). The environment to channel model mapping is shown in Table 3.1.

Table 3.1: Environment to Channel Model Mapping

Model	**Environment**
A	Flat fading (no multipath)
B	Residential
C	Residential / Small Office
D	Typical Office
E	Large Office
F	Large Space (indoors / outdoors)

The radio propagation loss model includes a path loss model and a shadowing model.

The path loss model consists of the free space path loss L_{FS} (slope of 2) up to a breakpoint distance d_{BP} and the slope becomes 3.5 after d_{BP}. Different d_{BP} are chosen for each channel model.

$$L(d) = L_{FS}(d) = 20\log_{10}(\frac{4\pi d}{\lambda}) \quad d \leq d_{BP} \tag{3.1}$$

$$L(d) = L_{FS}(d_{BP}) + 35\log_{10}(\frac{d}{d_{BP}}) \quad d > d_{BP} \tag{3.2}$$

where d is the transmit-receive separation distance in meter, and λ is the signal wavelength. The path loss model parameters are summarized in Table 3.2. In the table, the standard deviations of log-normal (Gaussian in dB) shadow fading are also included.

Table 3.2: IEEE802.11n & 802.11ac Path loss model parameters

Model	d_{BP} (m)	Slope before d_{BP}	Slope after d_{BP}	Shadow fading std. dev. (dB) before d_{BP} (LOS)	Shadow fading std. dev. (dB) after d_{BP} (NLOS)
A	5	2	3.5	3	4
B	5	2	3.5	3	4
C	5	2	3.5	3	5
D	10	2	3.5	3	5
E	20	2	3.5	3	6
F	30	2	3.5	3	6

3.1.2 IEEE 802.11ah

TGah channel model [39] consists of outdoor and indoor channel models which are based on 3GPP/3GPP2 spatial channel model (SCM) and TGn (MIMO) channel models, respectively. Besides, an additional outdoor device to device model is added for simulations requiring explicit modeling of such cases.

Outdoor Path Loss Models

The path loss models for TGah outdoor scenarios are based on Annex A.2- system simulation scenario of 3GPP TR 36.814 [40] and include two options:

1. Macro deployment antenna height is assumed 15m above rooftop and the path loss in [dB] is given by the formula

$$PL = 8 + 37.6 \log_{10}(d) \tag{3.3}$$

where d is in meter and the RF carrier is assumed at 900MHz. For other frequencies a correction factor of $21 \log 10(f/900MHz)$ should be added.

2. Pico/Hotzone deployment antenna height is assumed at roof top level and the path loss is given by

$$PL = 23.3 + 36.7 \log_{10}(d) \tag{3.4}$$

with adjustment for other frequencies as above.

The above formulas represent the median path loss. Deviation around this median to account for shadowing should be modeled by adding a random Gaussian variable with zero mean and standard deviation of 8dB for Macro deployments and 10dB for Pico deployments.

In addition, penetration loss of 10 dB should be added when simulating indoor reception with outdoor access points.

Outdoor Device to Device Path Loss Model

The antenna height is assumed 1.5m and the path loss in [dB] is given by the formula

$$PL = -6.17 + 58.6 \log_{10}(d) \tag{3.5}$$

where d is in meters and the RF carrier is assumed at 900MHz. The above formula represents the average path loss. Deviation around this average to account for shadowing should be modeled by adding a random Gaussian variable with zero mean and a standard deviation of 7.5dB.

Indoor Path Loss Model

TGah indoor path loss model can be modeled by directly scaling down the frequency operation of the TGn model which consists of the free space loss L_{FS} (slope of 2) up to a breakpoint distance and slope of 3.5 after the breakpoint distance. This is given in Equation (3.6) and (3.7), respectively.

$$L(d) = L_{FS}(d) = 20\log_{10}(\frac{4\pi d f_c}{c}) \quad d \leq d_{BP} \tag{3.6}$$

$$L(d) = L_{FS}(d) + 35\log_{10}(\frac{d}{d_{BP}}) \quad d > d_{BP} \tag{3.7}$$

where d, f_c and C are the transmit-receive separation distance in m, center carrier frequency set to 900MHz and speed of light.

The path loss model parameters are summarized in Table 3.3. In the table, the standard deviations of log-normal shadow fading i.e. $X_\sigma[dB] = N(0, \sigma_S)$ is included, These values were lower than the corresponding values in TGn model by 1 dB as a result of lower operation frequency.

Table 3.3: IEEE 802.11ah Path loss model parameters

Model	d_{BP} (m)	Slope before d_{BP}	Slope after d_{BP}	Shadow fading std. dev. (dB) before d_{BP} (LOS)	Shadow fading std. dev. (dB) after d_{BP} (NLOS)
A	5	2	3.5	2	3
B	5	2	3.5	2	3
C	5	2	3.5	2	4
D	10	2	3.5	2	4
E	20	2	3.5	2	5
F	30	2	3.5	2	5

The above model is valid for single floor scenario. In order to account for multiple-floor scenario, which is applicable to model A and B, floor attenuation factor FAF can be added as given in Equation (3.8)

$$L(d) = L_{FS}(d) + 35\log_{10}(\frac{d}{d_{BP}}) + \sum_{q=1}^{Q} FAF_q \quad d > d_{BP} \tag{3.8}$$

Where q is the floor index up to total number of floor, Q. FAF values for different number of floors is shown in Table 3.4. Note that if Equation (3.8) is used to characterize the path loss for multi-floor scenario, the associated standard deviations of log-normal shadow fading is also shown in Table 3.4.

Table 3.4: Average FAF and its associated standard deviation for the log normal shadowing effects for different number of floors.

Total number of floors,Q	$\sum_{q=1}^{Q} FAF_q$ (dB)	σ(dB)
1	12.9	7
2	18.7	2.8
3	24.4	1.7
4	27.7	1.5

3.1.3 Attenuation Consideration

Radio frequency (RF) signal strength is reduced as it passes through various materials. This effect is referred to as attenuation. As more attenuation is applied to a signal, its effective range will be reduced. The amount of attenuation will vary greatly based on the composition of the material the RF signal is passing through. For example, Table 3.5 from [41] shows the attenuation loss of different material type. It is extremely important to consider not just the type of obstruction, but how many obstructions the RF signal must pass through when designing a WiFi network.

Besides, a directional antenna offers an advantage over omni-directional antennas when it comes to attenuation as they are better able to penetrate different materials than traditional dipole antennas.

The bottom line to remember is that antenna selection and the physical environment of the facility have the biggest impact on range and coverage performance of an access point.

Table 3.5: Attenuation effects on different material types

Material	Typical Attenuation (Loss) at 5GHz
Cubical Wall	2dB
Drywall or Sheetrock	3dB
Brick Concrete or Block Wall	15dB
Elevator Shaft	10dB
Glass or Window	3dB
Concrete Floor	11dB

3.2 Channel Model Survey of Cell Network

In this section, the propagation loss model of different cell communication type is presented. The survey is referred from ITU-R Report M.2135 [42]. First, We will describe the test environments in cell communication. Next, the propagation loss model of each type of test environments will be illustrated. We have used the environment settings of the indoor hotspot scenario in the performance evaluation of proposed algorithm, and these models may be further applied to the design of cell network.

3.2.1 Test Environment

The purpose of the test environments is to challenge the radio interface technologies (RITs). Instead of constructing propagation models for all the possible International Mobile Telecommunications-Advanced (IMT-Advanced) operating environments, a smaller set of test environments is defined which adequately span the overall range of possible environments. The descriptions of these test environments may therefore not correspond with those of the actual operating environments.

For practical reasons, these test operating environments are an appropriate subset of the IMT-Advanced operating environments. While simple models might be adequate to evaluate the performance of individual radio links, more complex models are needed to evaluate the overall system-level reliability and suitability of specific technologies. For wideband technologies the number, strength, and relative time delay as well as the directions at Tx and Rx of the many signal components become important. For some technologies (e.g., those employing power control) these models must include coupling between all co-channel propagation links to achieve maximum accuracy. Also, in some cases, the large-scale (shadow fading) temporal variations of the environment must be modeled.

Base coverage urban test environment

The base coverage urban test environment focuses on large cells and continuous coverage. The key characteristics of this test environment are continuous and ubiquitous coverage in urban areas. This scenario will therefore be interference-limited, using macro cells (i.e. radio access points above rooftop level).

In urban macro-cell scenario mobile station is located outdoors at street level and fixed base station antenna clearly above surrounding building heights. As for propagation conditions, non- or obstructed line-of-sight is a common case, since street level is often reached by a single diffraction over the rooftop. The building blocks can form either a regular Manhattan type of grid, or have more irregular locations. Typical building heights in urban environments are over four floors. Buildings height and density in typical urban macro-cell are mostly homogenous.

The base coverage urban test environment is intended to prove that continuous, ubiquitous, and cost-effective coverage in built-up areas is feasible in the IMT-Advanced bands by the candidate IMT-Advanced RIT/SRITs. This scenario will therefore be interference-limited, using macro cells (i.e., radio access points above rooftop level) and still assume that the users require access to demanding services beyond baseline voice and text messages.

1. **Urban macro-cell scenario**

   In typical urban macro-cell scenario, the mobile station is located outdoors at street level and the fixed base station clearly above the surrounding building heights. As for propagation conditions, non- or obstructed line-of-sight are common cases, since street level is often reached by a single diffraction over the rooftop. The building blocks can form either a regular Manhattan type of grid, or have more irregular locations. Typical building heights in urban environments are over four floors. Buildings height and density in typical urban macro-cell are mostly homogenous.

The channel model for urban macro-cell scenario is called urban macro (UMa).

2. **Suburban macro-cell scenario (optional)**

   In suburban macro-cell scenario base stations are located well above the rooftops to allow wide area coverage, and mobile stations are outdoors at street level. Buildings are typically low residential detached houses with one or two floors, or blocks of flats with a few floors. Occasional open areas such as parks or playgrounds between the houses make the environment rather open. Streets do not form urban-like regular strict grid structure. Vegetation is modest.

   The channel model for suburban macro-cell scenario is called suburban macro (SMa).

Microcellular test environment

The microcellular test environment focuses on small cells and high user densities and traffic loads in city centers and dense urban areas. The key characteristics of this test environment are high traffic loads, outdoor and outdoor-to-indoor coverage. This scenario will therefore be interference-limited, using micro cells. A continuous cellular layout and the associated interference shall be assumed. Radio access points shall be below rooftop level. A similar scenario is used to the base coverage urban test environment but with reduced site-to-site distance and the antennas below rooftops.

The microcellular test environment focuses on smaller cells and higher user densities and traffic loads in city centers and dense urban areas, i.e., it targets the high-performance layer of an IMT Advanced system in metropolitan areas. It is thus intended to test the performance in high traffic loads and using demanding user requirements, including detailed modeling of buildings (e.g., Manhattan grid deployment) and outdoor-to-indoor coverage. A continuous cellular layout and the associated interference shall be assumed. Radio access points shall be below rooftop level.

1. **Urban micro-cell scenario**

   In urban micro-cell scenario the height of both the antenna at the BS and that at the user terminal (UT) is assumed to be well below the tops of surrounding buildings.

Both antennas are assumed to be outdoors in an area where streets are laid out in a Manhattan-like grid. The streets in the coverage area are classified as ”the main street”, where there is LoS from all locations to the BS, with the possible exception of cases in which LoS is temporarily blocked by traffic (e.g., trucks and busses) on the street. Streets that intersect the main street are referred to as perpendicular streets, and those that run parallel to it are referred to as parallel streets. This scenario is defined for both LoS and NLoS cases. Cell shapes are defined by the surrounding buildings, and energy reaches NLoS streets as a result of propagation around corners, through buildings, and between them.

The microcellular test environment includes outdoor and outdoor-to-indoor users: In the latter case the users are located indoors and Base Stations outdoors. Therefore the channel model for the micro-cellular test environment contains two parts, the outdoor part and the outdoor-to-indoor part.

The channel model for urban micro-cell scenario is called urban micro (UMi).

Indoor test environment

The indoor test environment focuses on smallest cells and high user throughput in buildings. The key characteristics of this test environment are high user throughput in indoor coverage.

1. **Indoor hotspot scenario**

   The indoor hotspot scenario consists of one floor of a building. The height of the floor is 6 m. The floor contains 16 rooms of 15 m $\times$ 15 m and a long hall of 120 m $\times$ 20 m. Two sites are placed in the middle of the hall at 30 m and 90 m with respect to the left side of the building (see Figure 3.1).

   The channel model for indoor hotspot scenario is called indoor hotspot (InH).

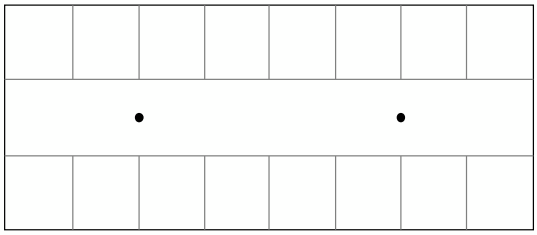

Figure 3.1: Sketch of indoor hotspot environment (one floor)

High-speed test environment

The high-speed test environment focuses on larger cells and continuous coverage. The key characteristics of this test environment are continuous wide area coverage supporting high speed vehicles. This scenario will therefore be noise-limited and/or interference-limited, using macro cells.

The high speed test environment is applicable to a wide-area system concept since it should allow for reliable links to high-speed trains of up to 350 km/hr or cars at high velocities. Repeater technology or relays (relaying to the same wide area system, IMT-2000, or to a local area system) can be applied in the vehicle, to allow for local access by the users.

1. **Rural macro-cell scenario**

   The Rural macro-cell scenario propagation scenario represents radio propagation in large areas (radii up to 10 km) with low building density. The height of the BS antenna is typically in the range from 20 to 70 m, which is much higher than the average building height. Consequently, LoS conditions can be expected to exist in most of the coverage area. In case the UT is located inside a building or vehicle, an additional penetration loss is experienced which can possibly be modeled as a (frequency-dependent) constant value. The BS antenna location is fixed in this propagation scenario, and the UT antenna velocity is in the range from 0 to 350 km/hr.

   The channel model for rural macro-cell scenario is called rural macro (RMa).

Simulation of relays

It is possible to simulate relay-based lay-outs with the proposed channel models by using models for the constituent hops of the multiple links. The link from a relay to a mobile station can be modeled with the same models as the conventional link from a base station to a mobile station. The links from base stations to relay stations can be modeled with conventional links.

3.2.2 Propagation Loss Model

Here we provide the details of the path loss models. For terrestrial environments, the propagation effects are divided into three distinct types: These are the path loss, the slow variation due to shadowing and scattering, and the rapid variation in the signal due to multipath effects.

The channel models are specified in the frequency range from 2 GHz to 6 GHz. For the rural macro-cell scenario (RMa), the channel model can be used for lower frequencies down to 450 MHz. The channel models are targeted for up to 100 MHz RF bandwidth.

Path loss models for the various propagation scenarios have been developed based on measurement results as well as results from the literature. The models can be applied in the frequency range of 2-6 GHz and for different antenna heights. The rural path-loss formula can be applied to the desired frequency range from 450 MHz to 6 GHz. The path loss models have been summarized in Table 3.7. Note that the distribution of the shadow fading is log-normal, and its standard deviation for each scenario is also given in Table 3.7.

The NLoS path loss model for scenario UMi is dependent on two distances, d_1 and d_2, in the case of the Manhattan grid. These distances are defined with respect to a rectangular street grid, as illustrated in Figure 3.2, where the UT is shown moving along a street perpendicular to the street on which the BS is located (the LoS street). d_1 is the distance from the BS to the center of the perpendicular street, and d_2 is the distance of the UT along the perpendicular street, measured from the center of the LoS street.

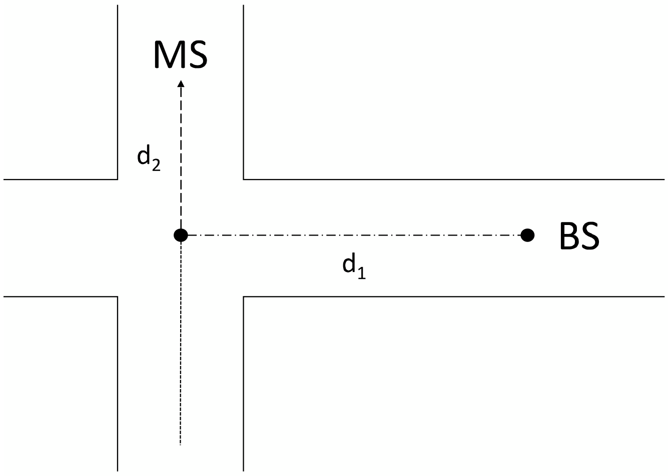

Figure 3.2: Geometry for d_1-d_2 path-loss model

Table 3.6: LoS probability as a function of distance (m)

Scenario	LoS probability as a function of distance, d (m)
InH	$P_{LoS} = \begin{cases} 1 & d \leq 18 \\ exp(-(d-18)/27) & 18 < d < 37 \\ 0.5 & d \geq 37 \end{cases}$
UMi	$P_{LoS} = \min(18/d, 1) \times (1 - exp(-d/36)) + exp(-d/36)$ (for outdoor users only)
UMa	$P_{LoS} = \min(18/d, 1) \times (1 - exp(-d/63)) + exp(-d/63)$
SMa	$P_{LoS} = \begin{cases} 1 & d \leq 10 \\ exp(-(d-10)/200) & d > 10 \end{cases}$
RMa	$P_{LoS} = \begin{cases} 1 & d \leq 10 \\ exp(-(d-10)/1000) & d > 10 \end{cases}$

The LoS probabilities are given in Table 3.6. Note that probabilities are used only for system level simulations.

Table 3.7: Cell communication path loss models

Scenario		**Path loss (dB)** f_c is given in GHz and distance is in m	**Shadow fading std. (dB)**	**Applicability range, antenna height default values (m)**
InH	LoS	$PL = 16.9\log_{10}(d) + 32.8 + 20\log_{10}(f_c)$	$\sigma = 3$	$3 < d < 100$ $h_{BS} = 3 - 6$ $h_{UT} = 1 - 2.5$
	NLoS	$PL = 43.3\log_{10}(d) + 11.5 + 20\log_{10}(f_c)$	$\sigma = 4$	$10 < d < 150$ $h_{BS} = 3 - 6$ $h_{UT} = 1 - 2.5$
UMi	LoS	$PL = 22.0\log_{10}(d) + 28.0 + 20\log_{10}(f_c)$ $PL = 40\log_{10}(d_1) + 7.8 - 18\log_{10}(h'_{BS}) - 18\log_{10}(h'_{UT}) + 2\log_{10}(f_c)$	$\sigma = 3$ $\sigma = 3$	$10 < d_1 < d'_{BP}$ $d'_{BP} < d_1 < 5000$ $h_{BS} = 10, h_{UT} = 1.5$ Explanations: see(1)
	NLoS	Manhattan grid layout: $PL = \min(PL(d_1, d_2), PL(d_2, d_1))$ where: $PL(d_k, d_l) = PL_{LoS}(d_k) + 17.9 - 12.5n_j + 10n_j\log_{10}(d_l) + 3\log_{10}(f_c)$ $n_j = max(2.8 - 0.0024d_k, 1.84)$ PL_{LoS}:path loss of scenario UMi LoS and $k, l \in \{1, 2\}$	$\sigma = 4$	$10 < d_1 + d_2 < 5000$ $w/2 < \min(d_1, d_2)$ $w = 20$ (street width) $h'_{BS} = 10, h_{UT} = 1.5$ When $0 < \min(d_1, d_2) < w/2$, the LoS PL is applied. Explanations: see(2)
		Hexagonal cell layout: $PL = 36.7\log_{10}(d) + 22.7 + 26\log_{10}(f_c)$	$\sigma = 4$	$10 < d < 2000$ $h_{BS} = 10$ $h_{UT} = 1 - 2.5$

Scenario		Path loss (dB) f_c is given in GHz and distance is in m	Shadow fading std. (dB)	Applicability range, antenna height default values (m)
	O-to-I	$PL = PL_b + PL_{tw} + PL_{in}$ Manhattan grid layout (θ known): $\begin{cases} PL_b = & PL_{Bl}(d_{out} + d_{in}) \\ PL_{tw} = & 14 + 15(1 - \cos(\theta))^2 \\ PL_{in} = & 0.5 d_{in} \end{cases}$ Hexagonal layout (θ unknown): $PL_{tw} = 20$ other values remain the same	$\sigma = 7$	$10 < d_{out} + d_{in} < 1000$ $0 < d_{in} < 25$ $h_{BS} = 10, h_{UT} = 1.5$ Explanations: see$^{(3)}$
UMa	LoS	PL=$22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c)$ PL=$40 \log_{10}(d_1)$+7.8−$18 \log_{10}(h'_{BS})$−$18 \log_{10}(h'_{UT}) + 2 \log_{10}(f_c)$	$\sigma = 4$ $\sigma = 4$	$10 < d < d'_{BP}$ $d'_{BP} < d_1 < 5000$ $h_{BS} = 25, h_{UT} = 1.5$ Explanations: see$^{(1)}$
	NLoS	$PL =$ 161.04−$7.1 \log_{10}(W)$+$7.5 \log_{10}(h) -$ $(24.37$−$3.7(h/h_{BS})^2) \log_{10}(h_{BS})$+ $(43.42$−$3.1 \log_{10}(h_{BS}))(\log_{10}(d)$−$3)$+ $20 \log_{10}(f_c) -$ $(3.2(\log_{10}(11.75 h_{UT})^2)$−$4.97)$	$\sigma = 6$	$10 < d < 5000$ h = average building height W = street width $h_{BS} = 25, h_{UT} = 1.5$ $W = 20, h = 20$ applicability ranges: $5 < h < 50$ $5 < W < 50$ $10 < h_{BS} < 150$ $1 < h_{UT} < 10$
SMa	LoS	PL_1=$20 \log_{10}(40\pi d f_c/3) +$ $\min(0.03h^{1.72}, 10) \log_{10}(d) -$ $\min(0.044h^{1.72}, 14.77) +$ $0.002 \log_{10}(h) d$	$\sigma = 4$	$10 < d < d_{BP}$ Explanations: see$^{(4)}$

Scenario		Path loss (dB) f_c is given in GHz and distance is in m	Shadow fading std. (dB)	Applicability range, antenna height default values (m)
		$PL_2 = PL_1(d_{BP}) + 40\log_{10}(d/d_{BP})$	$\sigma = 6$	$d_{BP} < d < 5000$ $h_{BS} = 35, h_{UT} = 1.5$ $W = 20, h = 10$ (applicability ranges of h,W,h_{BS},h_{UT} are same as in UMa NLoS)
	NLoS	$PL =$ $161.04-7.1\log_{10}(W)+7.5\log_{10}(h) -$ $(24.37-3.7(h/h_{BS})^2)\log_{10}(h_{BS})+$ $(43.42-3.1\log_{10}(h_{BS}))(\log_{10}(d)-3)+$ $20\log_{10}(f_c) -$ $(3.2(\log_{10}(11.75h_{UT})^2)-4.97)$	$\sigma = 8$	$10 < d < 5000$ $h_{BS} = 35, h_{UT} = 1.5$ $W = 20, h = 10$ (applicability ranges of h,W,h_{BS},h_{UT} are same as in UMa NLoS)
RMa	LoS	$PL_1 = 20\log_{10}(40\pi d f_c/3) +$ $\min(0.03h^{1.72}, 10)\log_{10}(d) -$ $\min(0.044h^{1.72}, 14.77) +$ $0.002\log_{10}(h)d$	$\sigma = 4$	$10 < d < d_{BP}$ Explanations: see(4)
		$PL_2 = PL_1(d_{BP}) + 40\log_{10}(d/d_{BP})$	$\sigma = 6$	$d_{BP} < d < 5000$ $h_{BS} = 35, h_{UT} = 1.5$ $W = 20, h = 5$ (applicability ranges of h,W,h_{BS},h_{UT} are same as in UMa NLoS)
	NLoS	$PL =$ $161.04-7.1\log_{10}(W)+7.5\log_{10}(h) -$ $(24.37-3.7(h/h_{BS})^2)\log_{10}(h_{BS})+$ $(43.42-3.1\log_{10}(h_{BS}))(\log_{10}(d)-3)+$ $20\log_{10}(f_c) -$ $(3.2(\log_{10}(11.75h_{UT})^2)-4.97)$	$\sigma = 8$	$10 < d < 5000$ $h_{BS} = 35, h_{UT} = 1.5$ $W = 20, h = 5$ (applicability ranges of h,W,h_{BS},h_{UT} are same as in UMa NLoS)

Notes to Table 3.7:

(1)

Break point distance $d'_{BP} = 4h'_{BS}h'_{UT}f_c/c$, where f_c is the center frequency (Hz), $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, and h'_{BS} and h'_{UT} are the effective antenna heights at the BS and the UT, respectively. The effective antenna heights h'_{BS} and h'_{UT} are computed as follows:

$h'_{BS} = h_{BS} - 1.0\text{m} \quad h'_{UT} = h_{UT} - 1.0\text{m}$

where: h_{BS} and h_{UT} are the actual antenna heights, and the effective environment height in urban environments is assumed to be equal to 1.0 m.

(2)

The distances d_1 and d_2 are defined below in Figure 3.2.

(3)

PL_b: basic path-loss, PL_{B1}: loss of UMi outdoor scenario, PL_{tw}: loss through wall, PL_{in}: loss inside, d_{out}: distance from BS to the wall next to UT location, d_{in}: perpendicular distance from wall to UT (assumed evenly distributed between 0 and 25 m), θ: angle between LoS to the wall and a unit vector normal to the wall.

(4)

Break point distance $d_{BP} = 2\pi h_{BS}h_{UT}f_c/c$, where f_c is the center frequency in Hz, $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, and h_{BS} and h_{UT} are the antenna heights at the BS and the UT, respectively.

Chapter 4

Problem Formulation

In this chapter, we will first describe the elements that need to be considered when designing a WLAN, and also present how we handle those elements in our WiFi network coverage planning platform. Next, we will describe an MILP model that will be used in Chapter 6 as a comparison to our algorithm, and depict a math model that our algorithm aims to optimize.

4.1 Design Specification

4.1.1 Environment Data

The most basic element demanded in wireless network planning is the specification of the target environment. An appropriate specification of the environment can help the designing program grasp the feature of such environment precisely, reduce the pre-processing time, and further improve the performance of optimization algorithms. The definition includes a floor plan and an applicable propagation model. A floor plan is a combination of walls which can be classified into different material, and is taken as an input for the propagation model. When the signal run across a wall, the signal strength should be decreased by a material-specific attenuation loss. With those environment data, the designing program can then estimate the signal coverage of a candidate AP.

In our planning platform, the environment is express as a 2-dimensional topology map

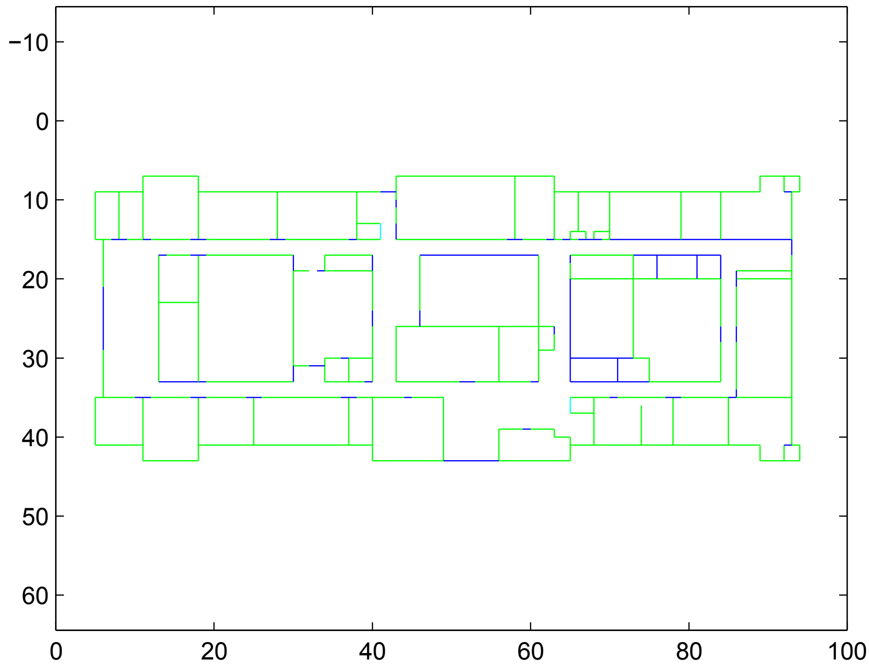

Figure 4.1: Topology map with grid resolution of 1m×1m

with a floor plan. Each point on the map represents a square grid, and the grid resolution can be adjusted by user's preference, such as 0.5m×0.5m, 1m×1m, 2m×2m, etc. A wall is defined as a line segment from a point to another with a material type. We provide six material types of brick wall, drywall, cubical wall, window, elevator, and floor. Each type of material has a corresponded attenuation in the propagation model, and the material types can be extended. An example of the topology map is illustrated as Figure 4.1 and the grid resolution is 1m×1m. Although this environment setting is only for the design of a single floor, extension to multiple floor design is possible. A multistory building can be constructed by stacking several 2D maps up, and the signal coverage can still be calculated.

4.1.2 Candidate Access Point

After the environment is defined, a set of candidate APs with their possible locations should be provided. To evaluate all of the possible installations of APs at all locations in the environment is not feasible in time consumption, and the resulted points might not fit the installation in real world. The specification of candidate APs can be used to restrict the potential search space in the first stage of design.

In our network planning platform, a candidate AP has a physical position on the 2D map with a defined height. In addition, it also has settings of the transmit power, the operating frequency, the bandwidth, the guard interval, and the supported stream number. Those information can be used to calculate the signal strength and the theoretical data rate supported by the candidate AP.

If a designer has the antenna radiation profiles of candidate APs, our platform can apply the profiles to the signal strength module for a more precise signal coverage.

4.1.3 User Demand

When the configuration of the environment data and the candidate APs is all ready, the next step is to specify additional constraints in the wireless network design. The constraints are the outcomes which a designer expect the network to achieve.

In our platform, we provide designers to set up the user demand with a throughput requirement map, which allows designers to specify the throughput requirement of every location on the map. The designers can also determine the priority of different target areas by configuring the priority map. The priority is used as a weighting for signal coverage, and our algorithm would satisfy the user demand of areas with high priority first. Areas with zero priority means that signal coverage over such area is not considered in our platform.

Moreover, in order to consider the effect of user competition, a people density map is needed in our platform. The people density map can aid the program to estimate the actual throughput of every point in a more realistic way. As long as the service area of a candidate AP is specified, we can translate the service area to the number of served users with the people density map. The number of served users affects the throughput in the service area when users compete for resources provided by serving AP. If every user divides the resources fairly, the theoretical throughput, which is referred from the MCS table of 802.11 standard, should also be divided by the number of the users to get a time-averaged throughput. Our algorithm compute the time-averaged throughput of every location on the map, and try to make the throughput reach the throughput requirement.

4.1.4 Planning Assumption

At last, we would like to explain the planning assumption for our study. We make two decisions —selection and channel assignment for APs— in our platform, and the results can be used as an initial configuration for wireless network deployment. We suppose that the designer has determined a set of candidate APs according to the practical situation of the target environment. The dynamic optimization of network parameters, such as transmit power and rate adaption threshold, is not the application of current platform.

We use the averaged theoretical throughput and the averaged signal-to-interference ratio (SIR) over the target area as performance measure. In the calculation of throughput, the traffic model of every potential client is assumed as saturation mode, which means the traffic is in full buffer state all the time. The computed throughput represents the max achievable data rate in the target network.

4.2 Math Model Formulation

In this section we would first introduce a MILP model that referred from [17, 27], and then we noted the deficiency of such model. Therefore, a modified math model that our algorithm aims to optimize is presented. Besides, we use the notation of a test point (TP) as a specified point in the target environment map. The set of TPs form a complete map for the target environment.

4.2.1 Multi-Criteria MILP Optimization Model

The purpose of the multi-criteria MILP optimization model is to minimize the channel overlap and keep the averaged total throughput above a specified value. The mathematic terminologies used in the MILP optimization model are summarized in Table 4.1.

The MILP model contains four types of binary variables: z_a, x_{at}, y_{ab}, and f_a^c. The

Table 4.1: Variables and coefficients in the MILP optimization model

Name	Domain	Interpretation
Sets		
A		Set of candidate APs
T		Set of TPs
C		Set of isolated channels
Variables		
z_a	$\{0,1\}^A$	AP a is selected or not
x_{at}	$\{0,1\}^{A\times T}$	AP a serves TP t or not
y_{ab}	$\{0,1\}^{\binom{A}{2}}$	AP a and AP b operate on the same channel or not
f_a^c	$\{0,1\}^{A\times C}$	AP a operates on channel c or not
Coefficients		
p_{at}	≥ 0	Received signal strength from AP a to TP t
$\phi(p_{at})$	≥ 0	Data rate from AP a to TP t (referred from MCS table)
N	> 0	Maximum number of APs to be selected
$\theta^{(c)}$	> 0	Clear channel assessment (CCA) threshold
$\theta^{(s)}$	> 0	receiver sensitivity
s_a	≥ 0	Size of service area for AP a
ω_{ab}	≥ 0	Estimated overlap between AP a and AP b
R	≥ 0	Desired average data rate

values of the binary variables can be determined by the MILP solving tool, and the consistency of each type of variable is maintained by the constraint in the model.

Before describing the complete MILP model, we have to define the overlap measure of APs in this model first. The following definitions estimate the areas that may be affected by co-channel interference and exposed terminal problem between two APs.

The size of service area of AP a is defined as the number of TPs within the transmission range of the AP a.

$$s_a \equiv \| \{t \in T | p_{at} \geq \theta^{(s)}\} \|$$

When AP a and AP b share the same channel, service from AP a to an associated TP t may be interfered by AP b if t is within the carrier sensing range of b. The number of TPs served by a and within the interference of b is:

$$\omega_{ab}^c \equiv \| \{t \in T | p_{at} \geq \theta^{(s)} \cup p_{bt} \geq \theta^{(c)}\} \|$$

The exposed terminal problem can be modeled by a similar definition. The problem can be expressed under the following conditions: Two stations at TP j and k connect to AP a and b respectively on the same channel, and the two stations are within the carrier sensing range of each other. In addition, the station at j is beyond the sensing range of AP b. Therefore, when AP a transmit data to the station at j, the data reception from AP b to the station at k may be hindered, because the station at k hears the CTS frame from the station at j but AP b does not. The number of TPs that may encounter this problem is modeled as:

$$\omega_{ab}^{u} \equiv \| \{(j,k) \in T \times T | p_{aj} \geq \theta^{(s)} \cup p_{bk} \geq \theta^{(s)} \cup p_{jk} \geq \theta^{(c)} \cup p_{bj} < \theta^{(c)}\} \|$$

Two of the scenario above can be used to define the overlap coefficients of candidate AP a and AP b, named ω_{ab}, in the optimization model:

$$\omega_{ab} \equiv \omega_{ab}^{c} s_b + \omega_{ba}^{c} s_a + \omega_{ab}^{u} + \omega_{ba}^{u}$$

Finally, the MILP optimization model can be described as the following equation set:

$$\min \sum_{(a,b)\in\binom{A}{2}} \omega_{ab} y_{ab} \tag{4.1a}$$

$$\text{s.t.} \quad \frac{1}{|T|} \sum_{(a,t)\in S} \phi(p_{at}) x_{at} \geq R \tag{4.1b}$$

$$f_a^c + f_b^c \leq 1 + y_{ab} \qquad \forall a, b \in A, c \in C \tag{4.1c}$$

$$\sum_{c\in C} f_a^c = z_a \qquad \forall a \in A \tag{4.1d}$$

$$x_{at} \leq z_a \qquad \forall (a,t) \in A \times T \tag{4.1e}$$

$$\sum_{a\in A} x_{at} \leq 1 \qquad \forall t \in T \tag{4.1f}$$

$$\sum_{a\in A} z_a = N \tag{4.1g}$$

The minimization of co-channel overlap is used as objective function (4.1a), and the average data rate is ensured to be at least R in Constraint (4.1b). Constraint (4.1c) make sure that the overlap variable y_{ab} is 1 if AP a and AP b operate on the same channel c.

Constraint (4.1d) states that every selected AP should only operate on one channel. Constraint (4.1e) and (4.1f) guarantee that a TP is only assigned to a selected AP. Constraint (4.1g) restricts the number of selected APs to N.

The model (4.1) formulate the optimization problem of WiFi network planning, and it can be solve by ready-made MILP problem solvers.

However, some definitions in the model is not suited enough for accurate estimation. For example, the overlap coefficient defined in this model overestimates conflicts between two APs, because the TPs within the carrier sensing range of an AP are not necessarily served by it. If there are many candidate APs around certain area, the overlap coefficient may not be able to distinguish proper set of APs that have less interference to each other. The effect of signal strength difference cannot be identified by the coefficient.

Furthermore, the throughput calculation in the model is too rough. The model ignore the effect of user competition on the real data rate. From Constraint (4.1b), the system throughput will be increased by a constant value $\phi(p_{at})$ if TP t is assigned to AP a. However, in real situation the actual throughput at a TP divides when the connecting AP serves more users. That is, the increase of of the total throughput is not a constant value. Also, the design of variable x_{at} does not fit the association of real situation. As a result, the model overestimates the throughput of its solution, and the resulted deployment may not reach the expected throughput of a designer.

4.2.2 Our Optimization Model

In this section, we present a more realistic calculation of throughput in our optimization model in contrast with the MILP model described in previous section. The mathematic terminologies used in our optimization model are summarized in Table 4.2.

In our optimization model, we deal with the AP selection problem and channel assignment problem separately. The model for AP selection problem only contains one type of binary decision variables z_a, which implies whether AP a is selected or not, and the variables z_a determine the values of the other variable x_{at}, which implies the association between AP a and TP t. In other words, we suppose that a station at TP t only associates to

Table 4.2: Variables and coefficients in our optimization model

Name	Domain	Interpretation
Sets		
A		Set of candidate APs
T		Set of TPs
C		Set of isolated channels
S_c		Set of the APs that operate on channel c
Variables		
z_a	$\{0,1\}^A$	AP a is selected or not
x_{at}	$\{0,1\}^{A\times T}$	AP a serves TP t or not
f_a^c	$\{0,1\}^{A\times C}$	AP a operates on channel c or not
Coefficients		
p_{at}	≥ 0	Received signal strength from AP a to TP t
$\phi(p_{at})$	≥ 0	Data rate from AP a to TP t (referred from MCS table)
ψ_t	≥ 0	Throughput requirement for TP t
η_a	≥ 0	Number of served people for AP a
d_t	≥ 0	People density for TP t
SIR_t	≥ 0	Signal to interference ratio (SIR) for TP t

the selected AP a which has the highest signal strength at TP t, so the association between AP and TP is ascertained once the selection of APs is made. The definition of x_{at} in our model is expressed as the following equation:

$$x_{at} = \begin{cases} 1 & \text{if} \quad p_{at} > p_{bt} \quad \forall b \in \{k \in A - \{a\} | z_k = 1\} \\ 0 & \text{otherwise} \end{cases}$$

Thus, we can specify the number of served users by the combination of a transition function defined from the people density map and the variable x_{at}. The equation below adds up the number of users which is served by AP a in order to approximate the total number of served users under AP a:

$$\eta_a = \sum_{t \in T} d_t \times x_{at}$$

Next, we divide the theoretical throughput value $\phi(p_{at})$ by the approximated number of users η_a to compute the averaged throughput under user competition. We make the time-averaged throughput satisfy the throughput requirement defined in the throughput requirement map in the criteria below:

$$\frac{\phi(p_{at})}{\eta_a} \geq \psi_t$$

Finally, we illustrate our optimization model for AP selection problem that estimate the throughput in a more precise form. The number of APs is used as objective function (4.2a), and the throughput requirement is defined in Constraint (4.2b).

$$\min \quad \sum_{a \in A} z_a \tag{4.2a}$$

$$\text{s.t.} \quad \frac{\phi(p_{at})}{\eta_a} \geq \psi_t \qquad \forall (a,t) \in A \times T | x_{at} = 1 \tag{4.2b}$$

After completing the AP selection process, we allocate the available channels to the selected APs to maximize the average SIR over all served area. The optimization model for channel assignment problem contains one types of binary decision variables f_a^c, which means that AP a operates on channel c. First, to specify the APs that would interfere with each other, we define the sets of serving APs that operate on the same channel c:

$$S_c = \{a \in A | f_a^c = 1, c \in C\}$$

After defining the serving APs on the same channel, we can calculate the SIR for every test point under the current deployment. The SIR at a test point is the ratio of the received power of the serving AP and the interference from other APs which operates on the same channel.

$$SIR_t = \frac{p_{at}}{\sum_{b \in S_c} p_{bt}}$$

At last, we illustrate our optimization model for channel assignment problem below. We attempt to maximize the averaged SIR value over all test points, which is used as the objective function (4.2).

$$\max \quad \frac{1}{\|T\|} \sum_{t \in T} SIR_t \tag{4.3}$$

Because the optimization model for AP selection problem (4.2) and channel assignment problem (4.2) can not be simply solved by an ready-made optimization tool and to examine every possible solution is too time-consuming, we employ a heuristic approach to solve them. The approach is described in Chapter 5.

Chapter 5

WiFi Network Planning Simulator and Algorithms

The function of the WiFi network planning platform is introduced in this chapter. The platform is first written in Matlab, and then it is rewritten to C-based library for practical usage. An application programming interface is also implemented in the C-based library, providing the front-end application an adequate result in little amount of time.

5.1 Module Overview

The network planning platform is composed of three parts: the signal strength module, the AP selection module, and the channel assignment module. Given the wall structure and the information of deployed AP(s), the signal strength module can produce the signal strength map for such deployment. Next, with the signal strength map, the AP selection module can determine favorable APs from a set of candidate APs. At last, with the list of selected APs, the channel assignment module can allocate available channels to those APs in order to optimize the SIR over the whole area.

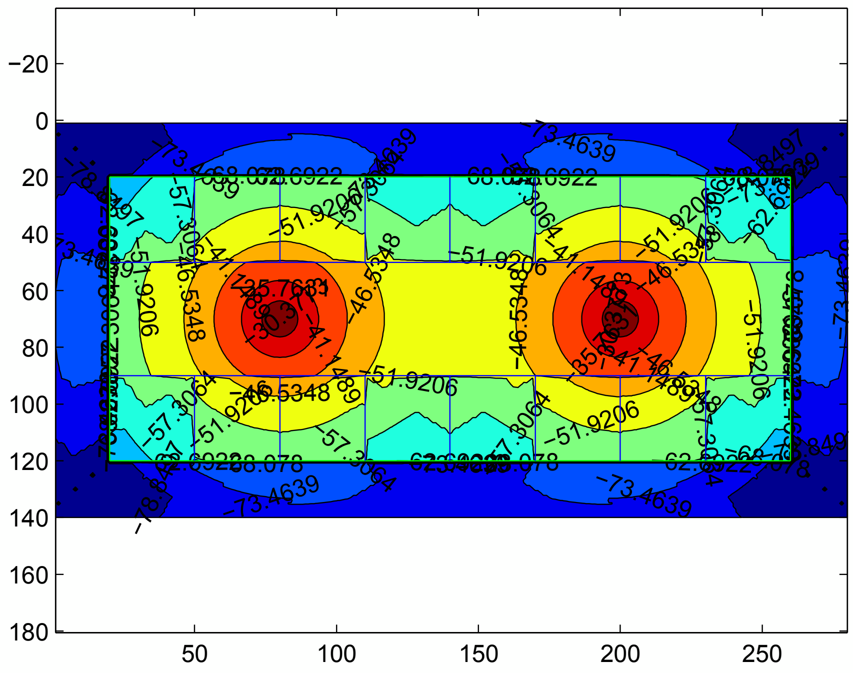

Figure 5.1: Signal strength map presented in contour map

5.2 Signal Strength Module

The aim of signal strength module is to produce the signal strength map with topology information. A map with wall structure and type, AP settings with transmit power and location, and system parameters — such as operating model, carrier frequency, receiving height, and receiver sensitivity — are needed to create signal strength map. For every point on the map, we use the surveyed 802.11 path loss model to calculate the signal strength of that location. The elements of path loss model are path loss, penetration loss, and antenna gain. The signal strength values of every point is stored in a 2D array and can be used to show a contour map of signal strength (Figure 5.1).

Besides, the parameter called receiver sensitivity is used to skip the calculation of a signal strength value which is too small. When the signal strength value is below the receiver sensitivity at a point, we set the signal strength value of such point to be 1 dB below the receiver sensitivity.

We use multi-wall model with a 3D location setting for convenience and effectiveness in implementation. Although the signal strength map only presents the signal strength

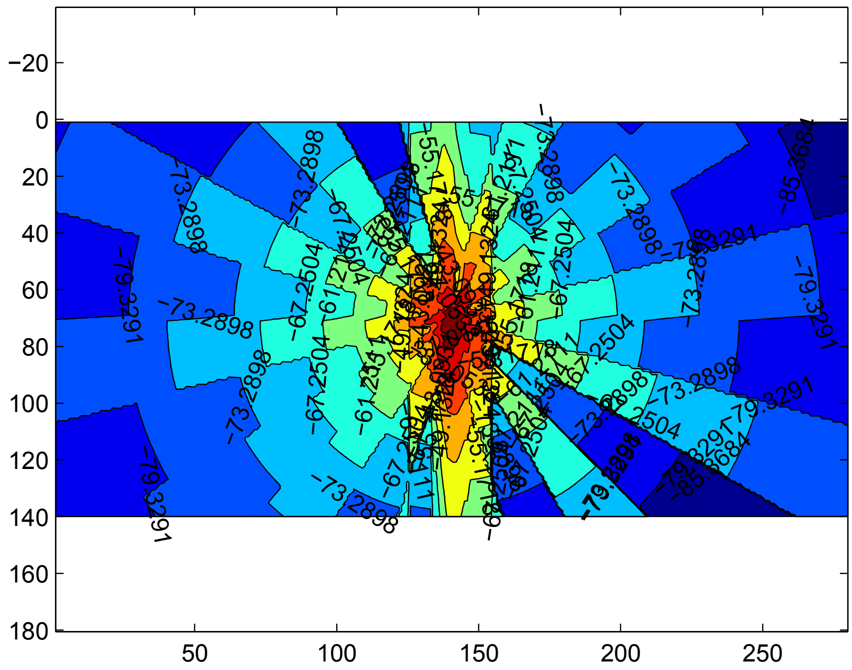

Figure 5.2: Signal strength map when the antenna is on x+ direction

at the receiving height, the effect of AP's height is also taken in consideration. When calculating the path loss from an AP to current position, we only consider the LoS distance. The attenuation loss is added if the LoS path runs across a wall. The effect of diffraction is omitted for the simplicity of computation.

The antenna gain is also taken into consideration if such option is turned on. For each candidate AP, the antenna direction could be set to 3 predefined type: x+, y+, or z+. The signal strength module could apply provided radio pattern data to compute the signal strength under different antenna direction configuration. An example of the signal strength map under different antenna direction with the same radio pattern data is shown in Figure 5.2, Figure 5.3, Figure 5.4.

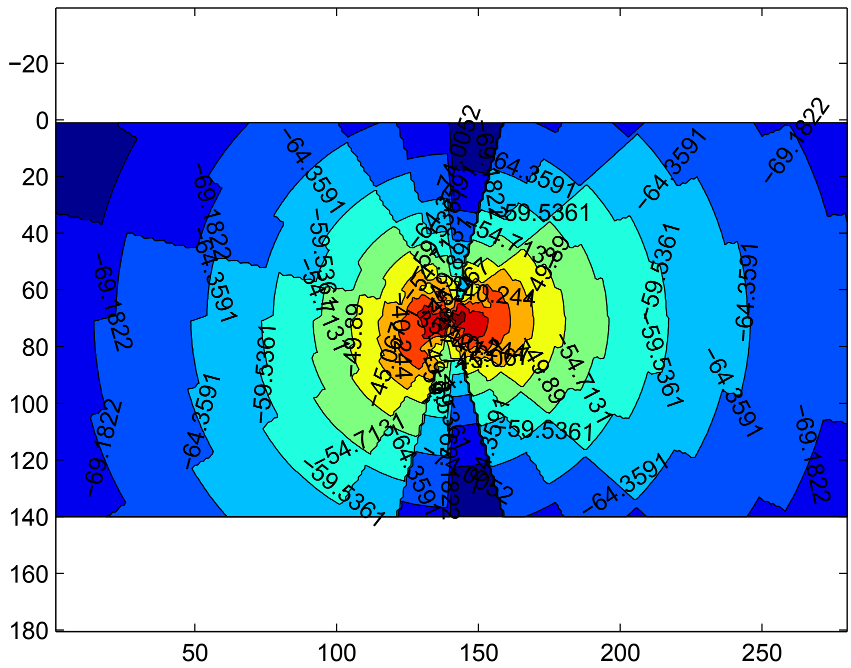

Figure 5.3: Signal strength map when the antenna is on y+ direction

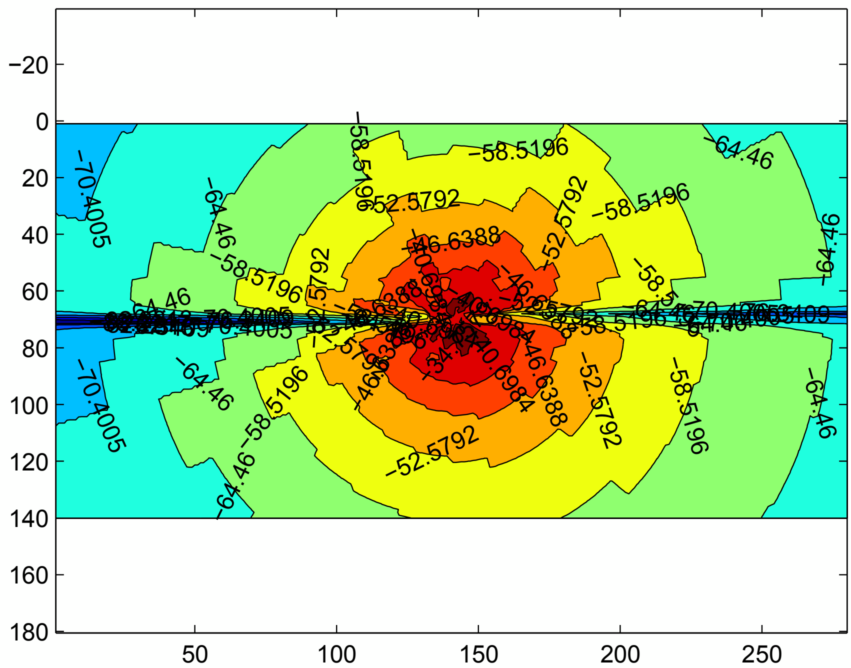

Figure 5.4: Signal strength map when the antenna is on z+ direction

5.3 AP Selection Module

The aim of AP selection module is to select favorable APs for maintaining better coverage, to reduce AP amount from all possible APs, and to keep the throughput demand. To activate the selection process, the module need a set of available APs with operating information and locations, the topology information, an area priority map, a people density map, and a throughput requirement map. The algorithm contains three phase: coverage prediction, station elimination, and throughput guarantee.

5.3.1 Phase I: Coverage Prediction

In this phase, we compute the weighted average coverage for each candidate AP. The weighted average coverage for each AP can be used as an importance measure when selecting the candidate APs.

The process to calculate the weighted average coverage is described below. First, we use signal strength module to create signal strength map for each AP in the candidate AP list. Second, the signal strength map is used to produce the basic coverage map. The coverage map implies whether an AP can provide adequate signal strength to every specified location. In the coverage map, the value is set to be 1 for a grid on the map with received signal strength larger than the max needed receive power, which is sufficient to provide the highest MCS. In contrast, the value is set to be 0 for a grid with the received signal strength smaller than the min needed receive power, which is needed to provide the lowest MCS. If the signal strength is between the two thresholds, the value for the grid is interpolated between 0 and 1 according to the received power.

Next, we create the weighted coverage map from the coverage map and the priority map. We scale the priorities of the priority map to be between 0 and 1, and then multiply values of the coverage map with values of such scaled priority map point by point to create the weighted coverage map. The transition of priority and signal strength to weighted coverage value is presented in Figure 5.5.

Finally, all values in the effective area of the weighted coverage map are averaged to retrieve the weighted average coverage for the AP. The effective area is defined as the

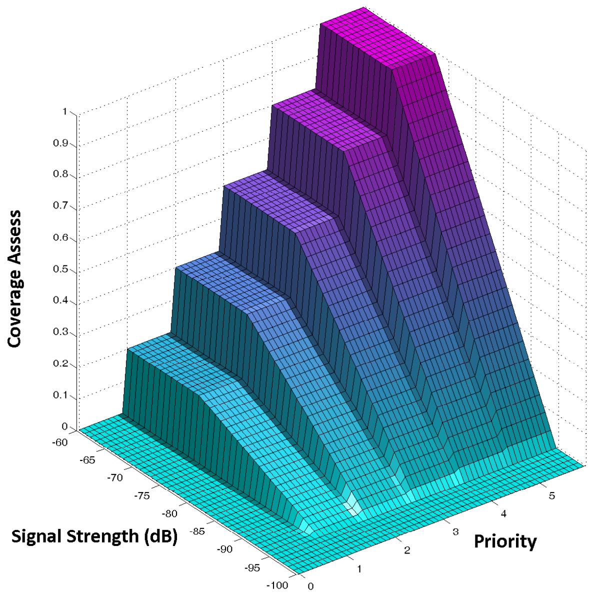

Figure 5.5: Weighted Coverage Transition Function

nonzero priority area. The process that we calculate the weighted average coverage from the coverage map and the priority map can be express as the following equation.

$$WeightedCoverage(AP) = \frac{\sum_{(x,y)\in A_{effective}} CoverageMap(x,y) \times ScaledPriorityMap(x,y)}{\|A_{effective}\|}$$

5.3.2 Phase II: Station Elimination

In this phase, we eliminate less important APs from the candidate AP list. The aims are to reduce interference from stations near-by, and thus to reduce installation cost.

First, we iteratively find AP with large overlapping. To specify, if the mean absolute power difference between two APs is lower than certain threshold in every priority area, the two APs are said with large overlapping. The mean absolute power difference threshold at minimum and maximum priority is needed to obtain the power difference level for all priority, and the power difference level is assigned in proportion. The relation between mean absolute power difference and priority is presented in Figure 5.6.

After the overlapping condition is computed for all AP pairs, we add AP pairs with

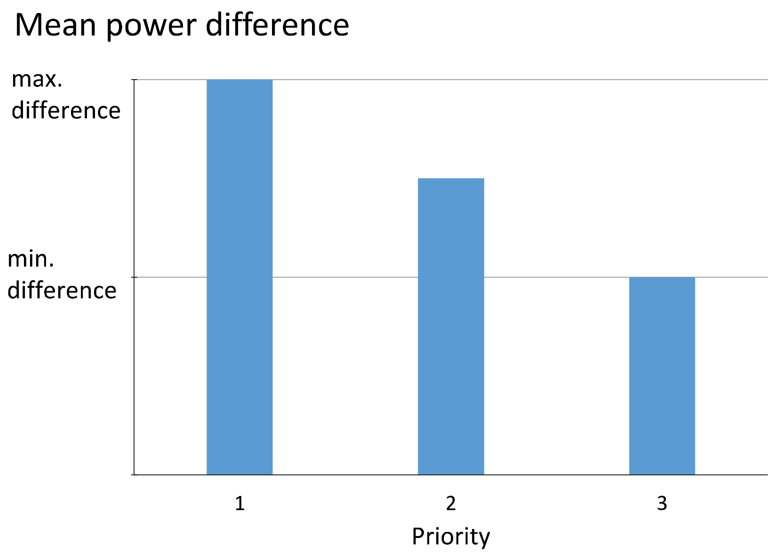

Figure 5.6: Relation of power difference and priority

large overlapping into an overlapping AP group. Next, we keep the most important AP in each group and eliminate other APs, which are less important. After such process, the remaining APs could still maintain sufficient coverage on the topology.

5.3.3 Phase III: Throughput Guarantee

In this phase, we add APs to the selected AP list generated from Phase II in order to satisfy the throughput requirement. The purpose of this phase is to satisfy the throughput need after we maintain basic coverage with Phase II.

First, we construct an allocation map for the selected AP list. Every point on the map is allocated to the AP that has the highest signal strength. Second, for every point, the signal strength of serving AP is converted into theoretical data rate according to the MCS table from 802.11 standard. Next, we compute the averaged theoretical throughput under user competition for each point.

Finally, we can examine whether the averaged throughput meets the throughput requirement point by point. If the constraint is not met under certain serving AP, we add less important AP respectively into the selected AP list. An AP is added back when it can share the most users from such serving AP to reduce the traffic load. Because the serving users is shared by the newly added AP, the time averaged throughput under the insuffi-

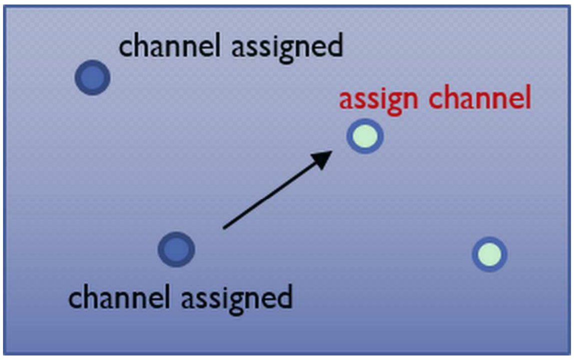

Figure 5.7: Channel Allocation Order

cient AP is also raised to meet the requirement. Whenever an AP is added back to the list, we have to restart from the first step to construct a new allocation map for the updated list. The process ends when every point is visited and no AP can be added back to enhance the throughput performance.

5.4 Channel Assignment Module

The aim of channel assignment module is to allocate available channels to the APs in the selected AP list, and optimize the SIR over the whole area. The selected AP list, topology information, signal strength information, average weighted coverage of APs (from AP location module Phase I), and an allocation map for the selected APs (from AP selection module Phase III) are needed in this module.

We use a greedy approach to assign channel. First, we start allocating channel from AP with highest weighted coverage, and continue to the next AP with lowest path loss. The allocating process is shown in Figure 5.7.

When the number of non-overlapping channels is exhausted, two implemented algorithms are used separately to allocate the channels. In the first algorithm called Received Power Algorithm, the received power from all the APs which are already assigned a channel is evaluated at the next AP. The channel with lowest received power is then assigned to this AP. In the second algorithm called Subarea Interference Algorithm, the averaged SIR over the served area from all the APs which are already assigned a channel is evaluated at the next AP. The channel with highest averaged SIR over served area is then allocated to this AP. The process continues to the next AP with lowest pathloss and so on.

After all selected APs have been assigned with a specified channel, we evaluate the two solution set by computing the averaged SIR over whole area. The solution set with the higher averaged SIR is adopted.

5.5 C-based Library Introduction

The WiFi network planning platform has been rewritten to C-based library, and a application programming interface is implemented. We have also implemented a test software to validate the library. A screenshot of the test software is shown in Figure 5.8.

The data flow of the C-based library is shown in 5.9. With the environment data and the operating AP list, the signal strength module can generate the resulted signal strength map. In order to satisfy the real-time computation requirement of signal strength map whenever an AP is added, deleted, or dragged to a new location in the front-end application, the signal strength module can also provide a rough output first before computing all the signal strength result. If the designer activates the network planning process, the output of the signal strength module is then used as input for the AP selection module. The AP selection module utilize the signal strength map, the priority map, the throughput constraint map, and the people density map to select favorable APs and export the result to the channel assignment module. Therefore, the channel assignment module generates an allocation plan for those selected APs. At last, the AP selection plan with channel allocation is presented to the designer.

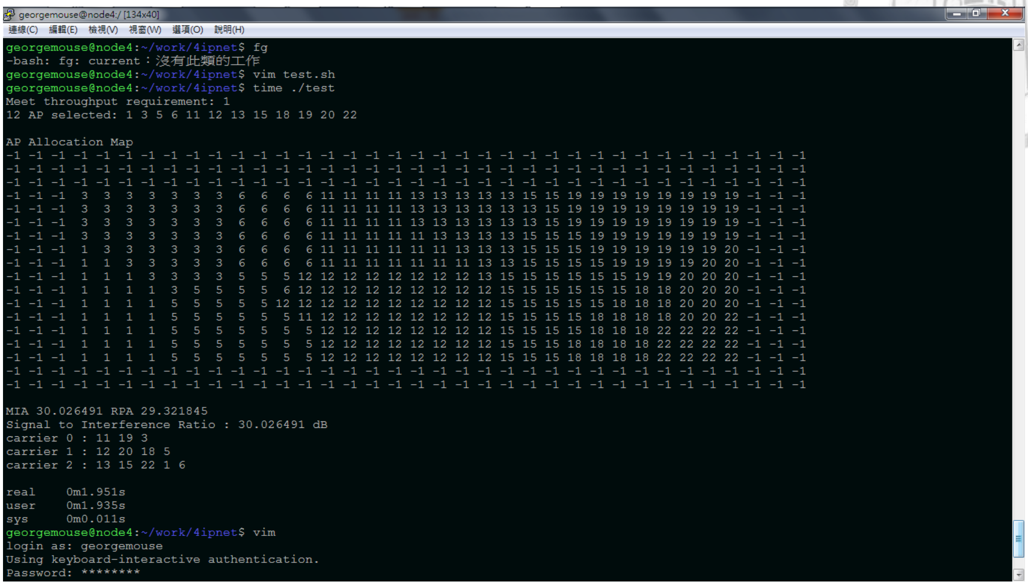

Figure 5.8: Screenshot of test software from C-based library

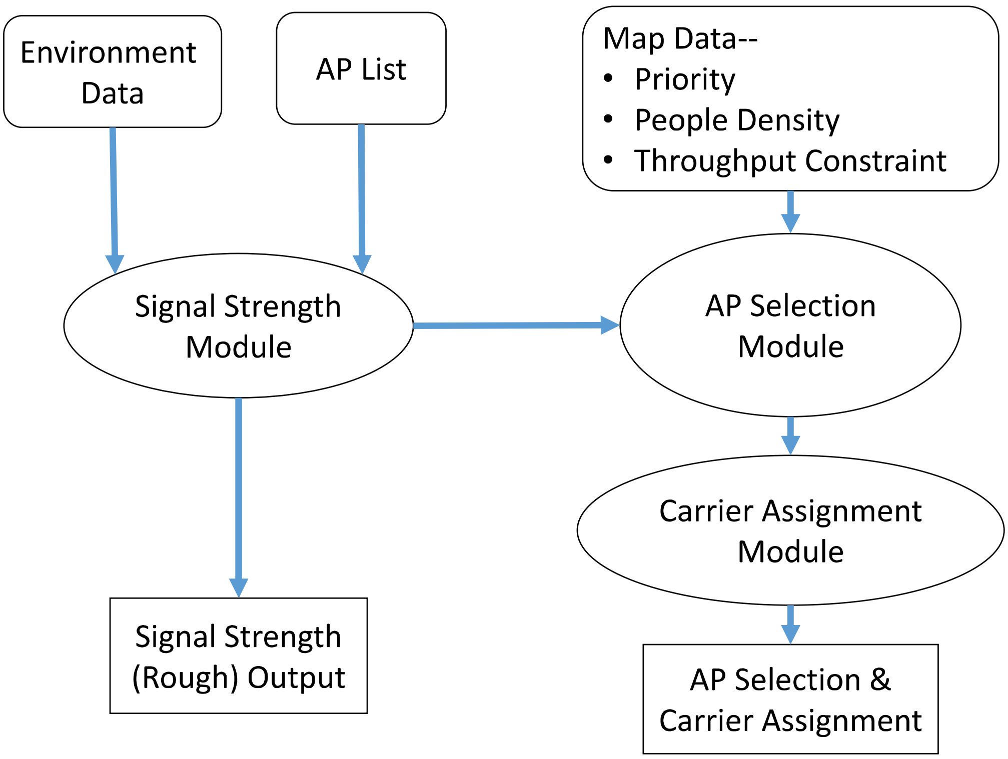

Figure 5.9: Data Flow of C-based library

Chapter 6

Evaluation

We have conducted two experiments to examine the performance of the network coverage planning platform.

6.1 Experiment for Indoor Hotspot Scenario

6.1.1 Experiment Setup

The system parameters for indoor hotspot (InH) scenario are listed in Table 6.1.

The topology is derived from ITU-R Report M.2135 [42], which is the indoor hotspot scenario mentioned in Section 3.2. The floor contains 16 rooms of 15 m $\times$ 15 m and a long hall of 120 m $\times$ 20 m. The scale of the map is 2X, which means a point on the map is equal to a 0.5m-sided square grid.

There are 25 candidate APs, and the topology map with candidate AP locations is presented in Figure 6.1. In the topology, the green lines are concrete wall and blue lines are drywalls and doors. The blue circles are the locations of candidate APs. Every black number attached by the blue circle is the candidate AP's height, and the red number is the candidate AP's index.

The topology is divided into three parts: the rooms, the long hall, and the remaining area. In the rooms, the area priority is 2, the throughput constraint is 15 Mbps, and the people density is 0.04 people / m², which implies that there are 9 people uniformly dis-

Table 6.1: System parameter for InH scenario

Map Size	140×280 points
Scale	2X (square grid = 0.5m×0.5m)
Candidate station number	25
Wall number	20
Priority map area number	3
Path loss model	802.11n model D (Typical office)
AP signal power	21 dBm
Carrier frequency	2.4 GHz
Stream number	2
Bandwidth	40 MHz
Guard interval	400 ns
Receive sensitivity	-95 dB
Max needed receive power	-70 dB (MCS 15)
Min needed receive power	-95 dB (MCS 0)
Mean power difference threshold at min priority	20 dB
Mean power difference threshold at max priority	10 dB
Channel number	3

tributed in each 15 m × 15 m room. In the long hall, the area priority is 1, the throughput constraint is 5 Mbps, and the people density is 0.02 people / m², which implies that there are 48 people uniformly distributed in the 120 m × 20 m hall. The area priority, throughput constraint, people density is set to be all zero for the remaining area. The area priority map, throughput constraint map, people density map is shown respectively in Figure 6.2, Figure 6.3, and Figure 6.4.

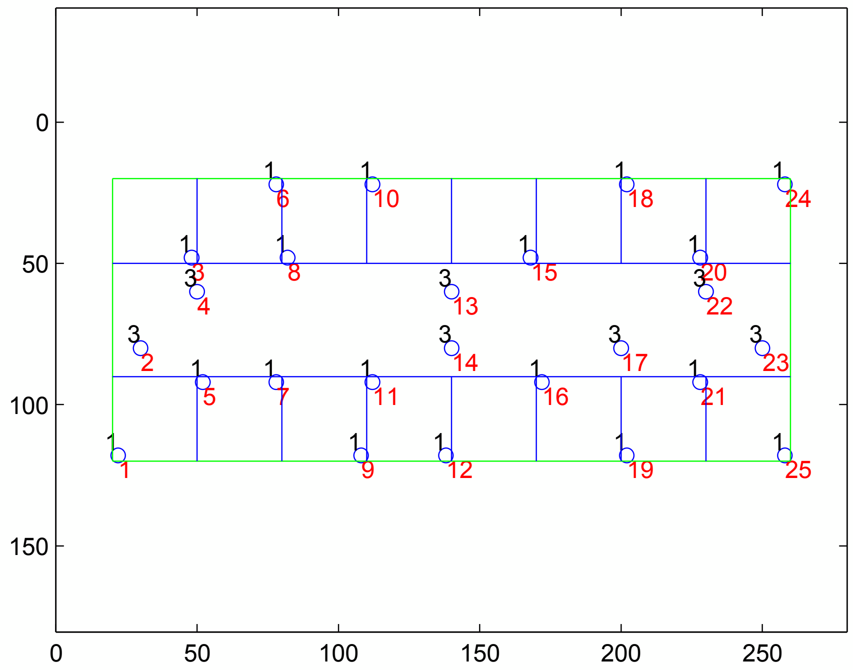

Figure 6.1: Topology map with candidate APs' information for InH scenario

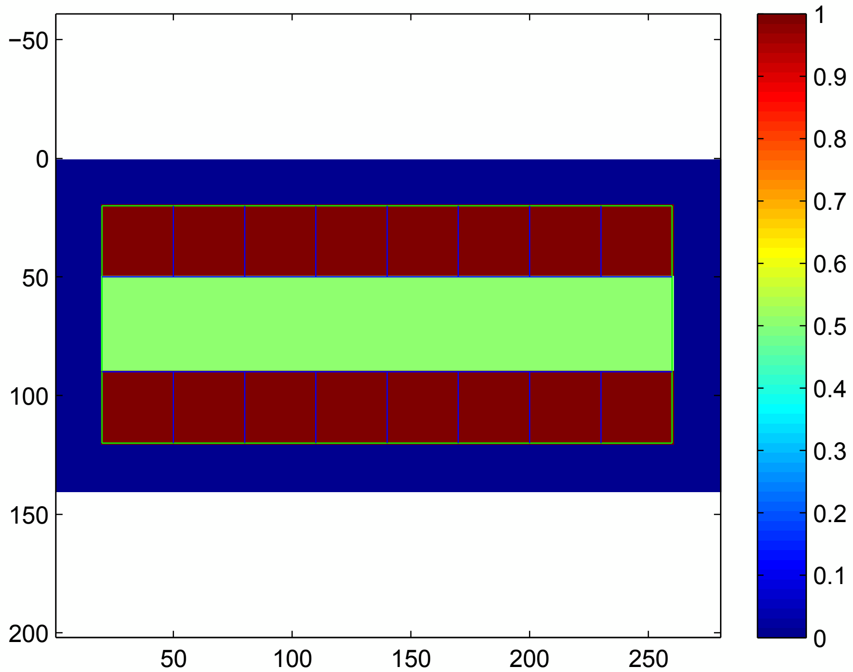

Figure 6.2: Priority map for InH scenario

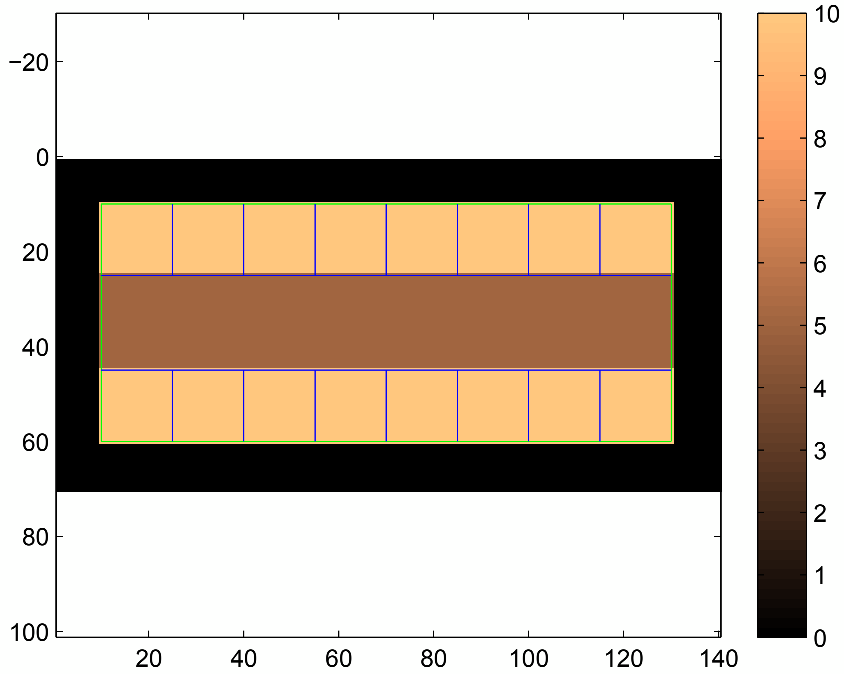

Figure 6.3: Throughput requirement map for InH scenario

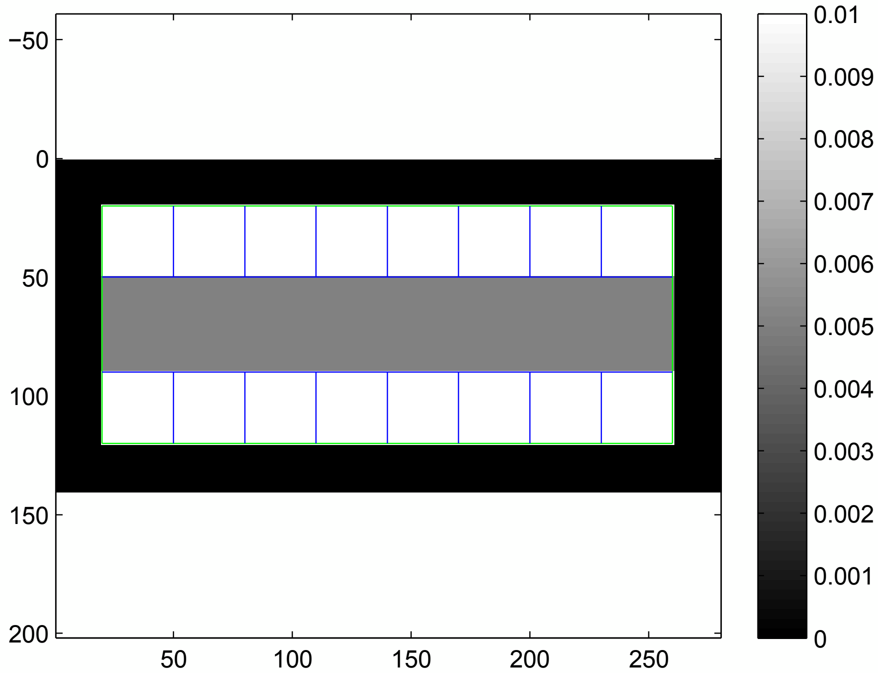

Figure 6.4: People density map for InH scenario

6.1.2 Result and Comparison

The result of the InH experiment is presented in this section. As Figure 6.5, 10 APs are selected in this scenario. The resulted signal strength map of selected APs is shown in Figure 6.7 and the distribution of their served area is presented in Figure 6.8. The channel allocation condition determined by the channel assignment module is demonstrated in Figure 6.9. The received power algorithm wins by 22.9575 dB of averaged SIR, and the SIR distribution is shown in 6.11. Finally, the throughput distribution for such deployment is shown in Figure 6.13.

When adding back candidate APs to satisfy all the throughput demands on the map, we select the candidate AP which can share the most users from insufficient serving AP. Because we have selected the APs with large coverage score as initial solution set, added candidate AP are less possible to share too many users that added AP cannot afford. Such process can utilize less AP to satisfy the throughput demand, and hence improve the SIR performance.

If we add the candidate AP which overlaps the insufficient serving AP most into the initial solution set as a compared algorithm, the resulted selection of 12 APs is shown in Figure 6.6. The channel allocation status is shown in Figure 6.10, the resulted SIR distribution is illustrated in Figure 6.12, and The resulted throughput distribution is as Figure 6.14. From the CDF comparison of effective area's SIR in Figure 6.15, we found that the SIR performance of our algorithm implemented in the planning platform is better than the one of compared algorithm for most of the grids on the map. Moreover, the averaged SIR of the compared algorithm is 19.1103 dB, which is much worse than the selection method of our algorithm. It is because the selection process of the compared algorithm chooses too many nearby AP, and hence the interference from nearby AP is too high. From the CDF comparison of effective area's throughput excess in Figure 6.16, we can also notice that the resulted throughput is unnecessarily too high for the compared algorithm.

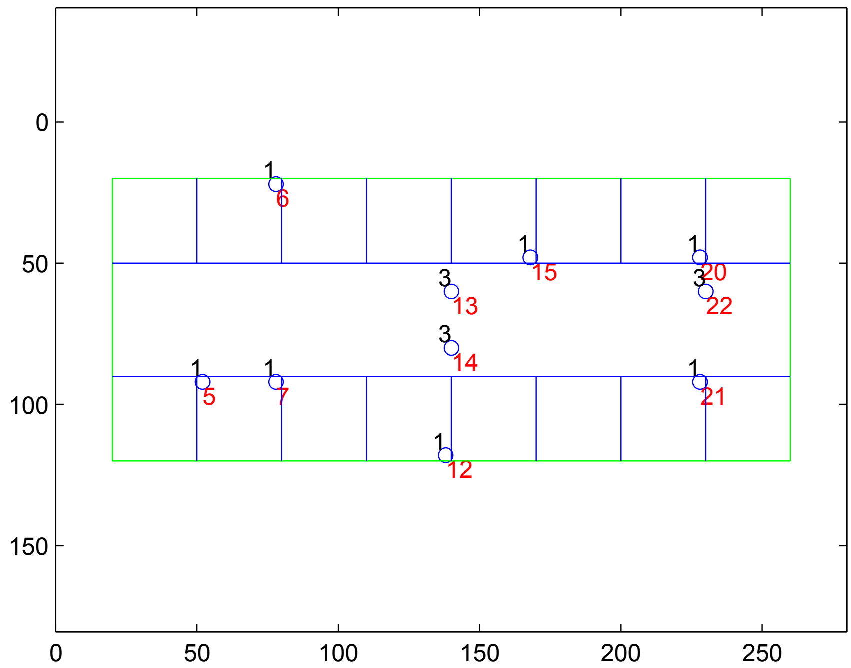

Figure 6.5: Selected APs for InH scenario

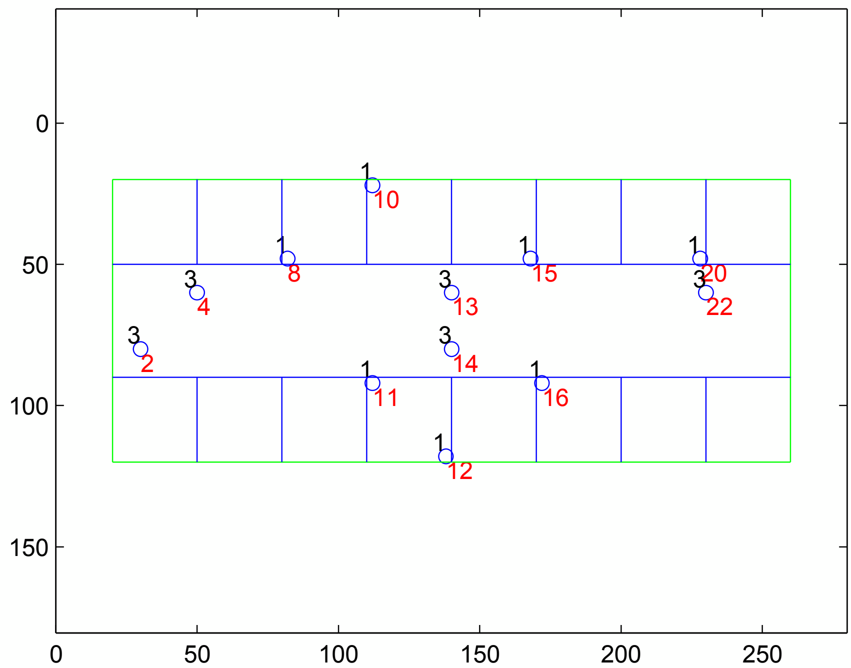

Figure 6.6: Selected APs of compared algorithm for InH scenario

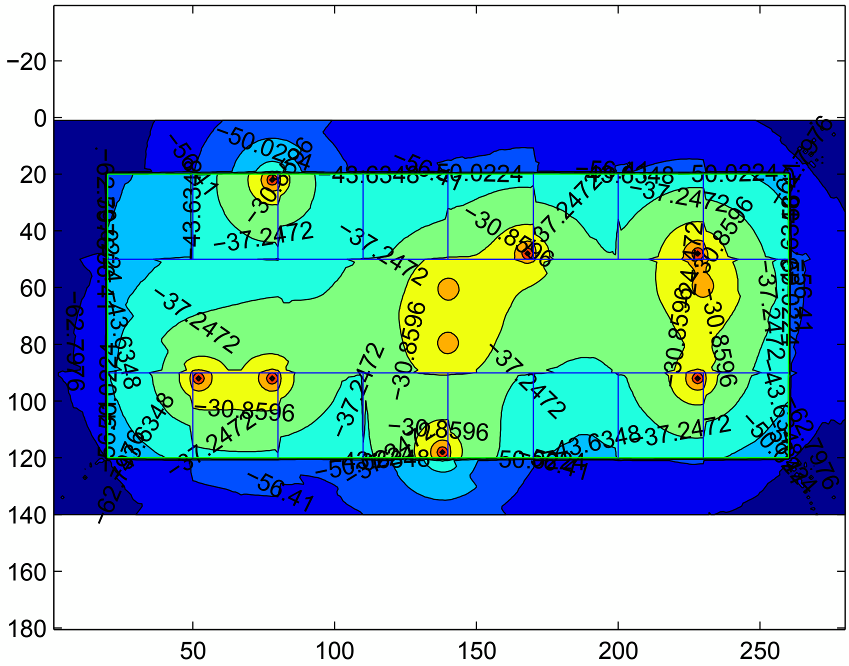

Figure 6.7: Signal strength contour map of selected APs for InH scenario

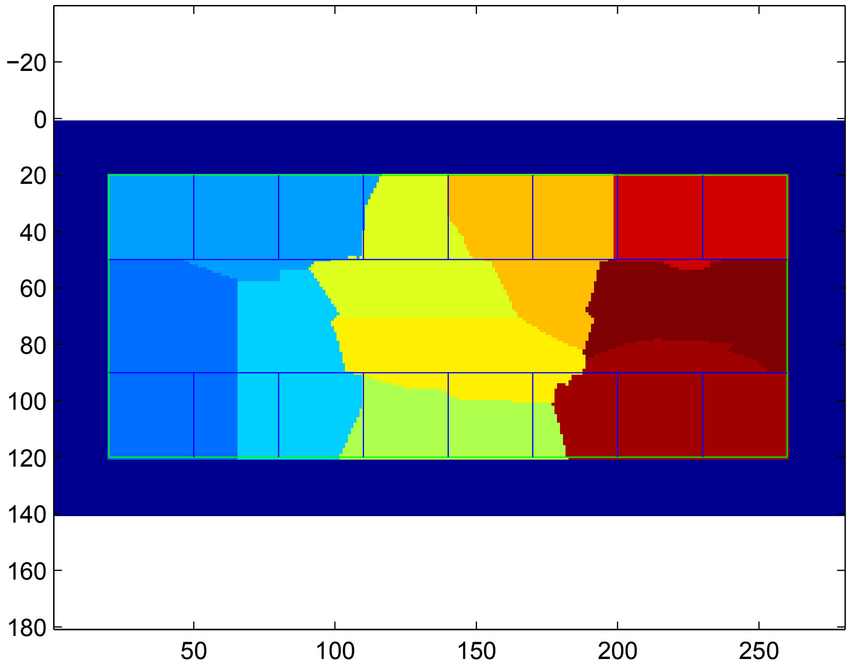

Figure 6.8: Allocation map of selected APs for InH scenario

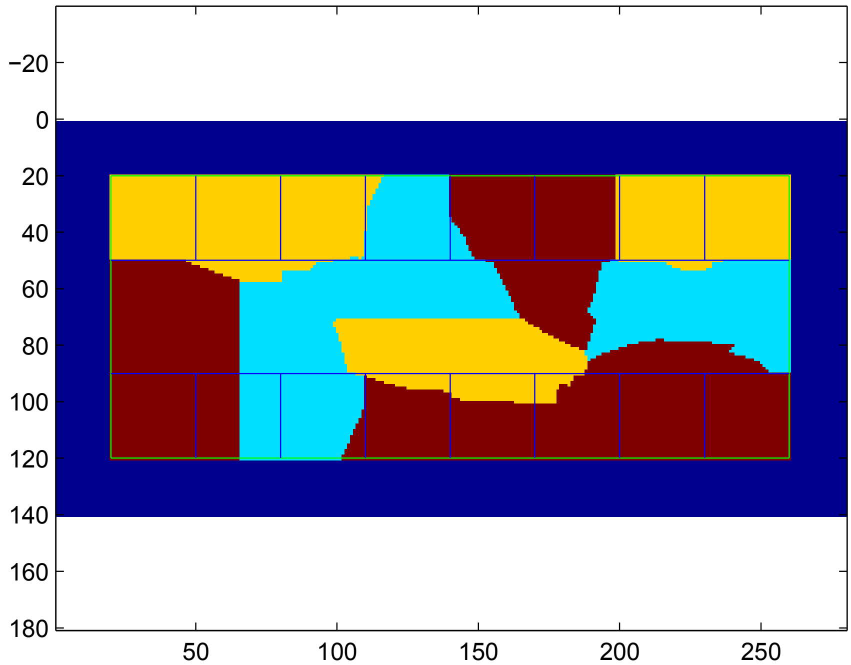

Figure 6.9: Channel allocation map of selected APs for InH scenario

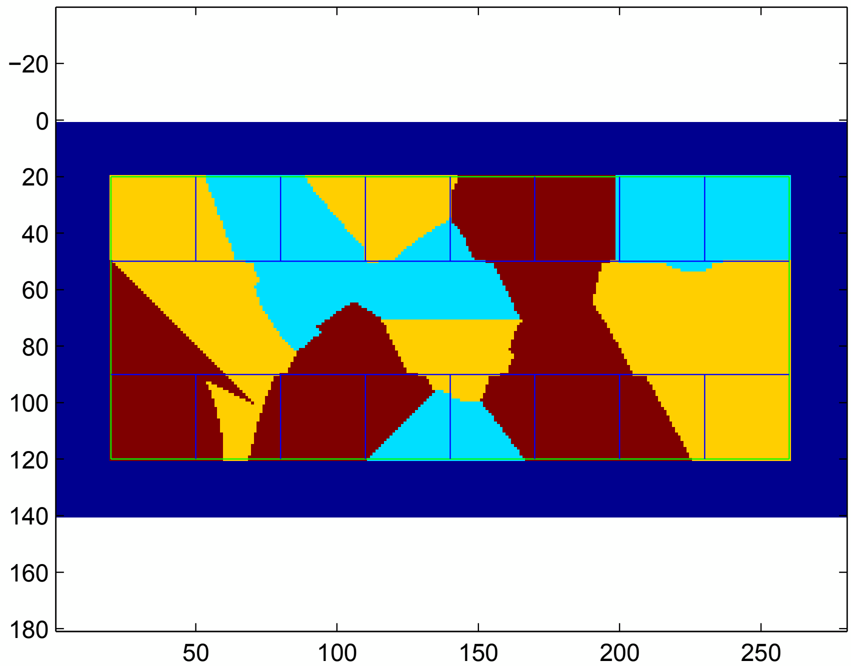

Figure 6.10: Channel allocation map of compared algorithm of selected APs for InH scenario

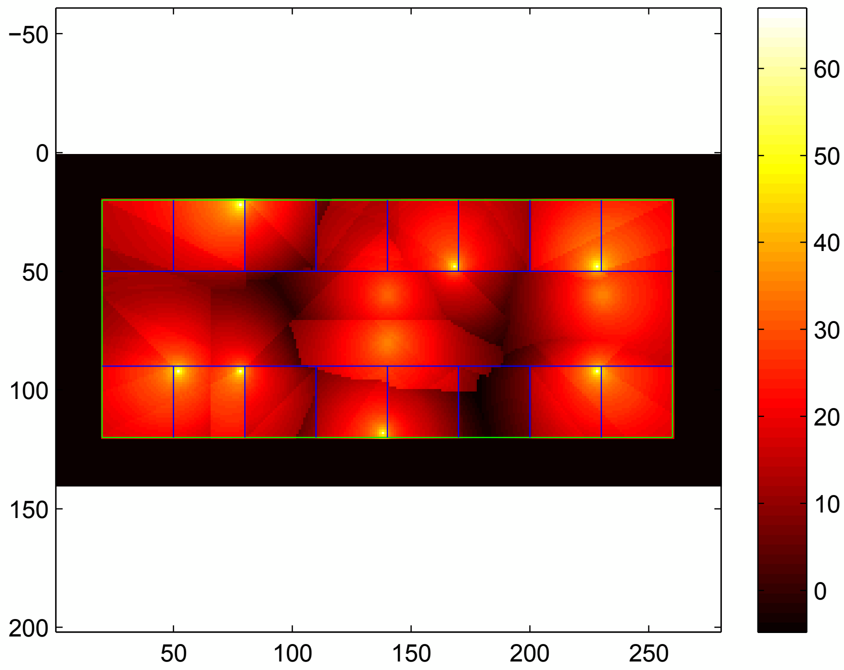

Figure 6.11: SIR map for InH scenario

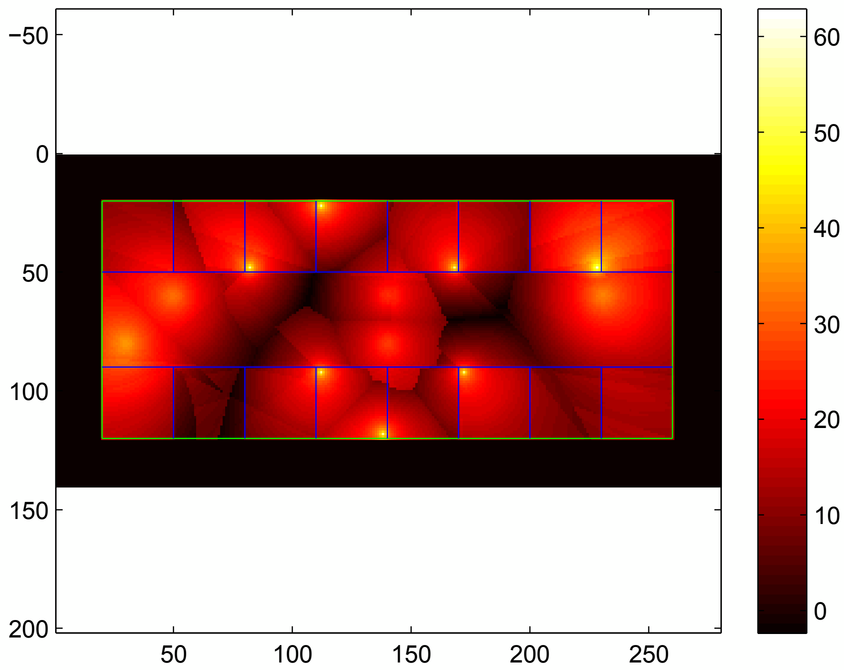

Figure 6.12: SIR map of compared algorithm for InH scenario

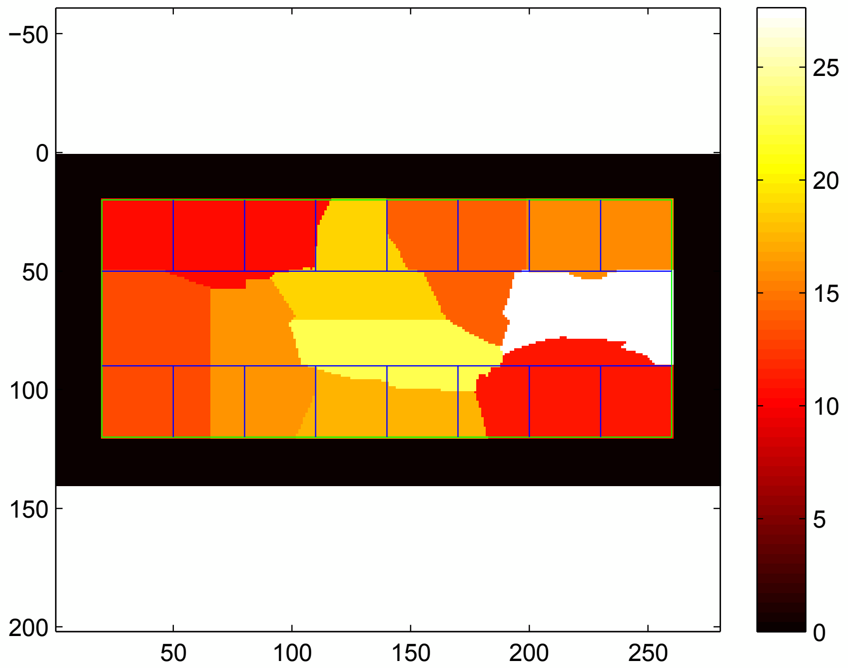

Figure 6.13: Theoretical throughput map for InH scenario

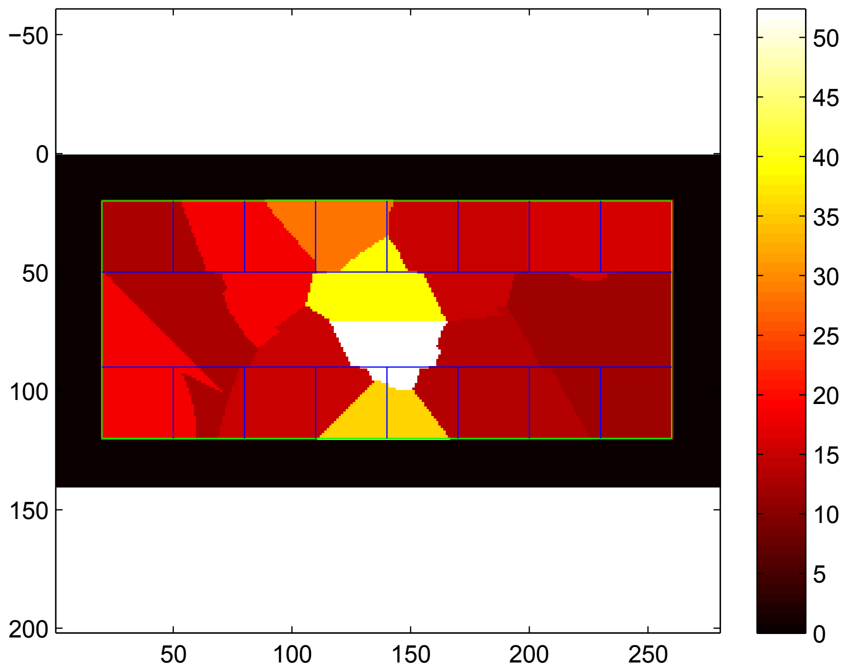

Figure 6.14: Theoretical throughput map of compared algorithm for InH scenario

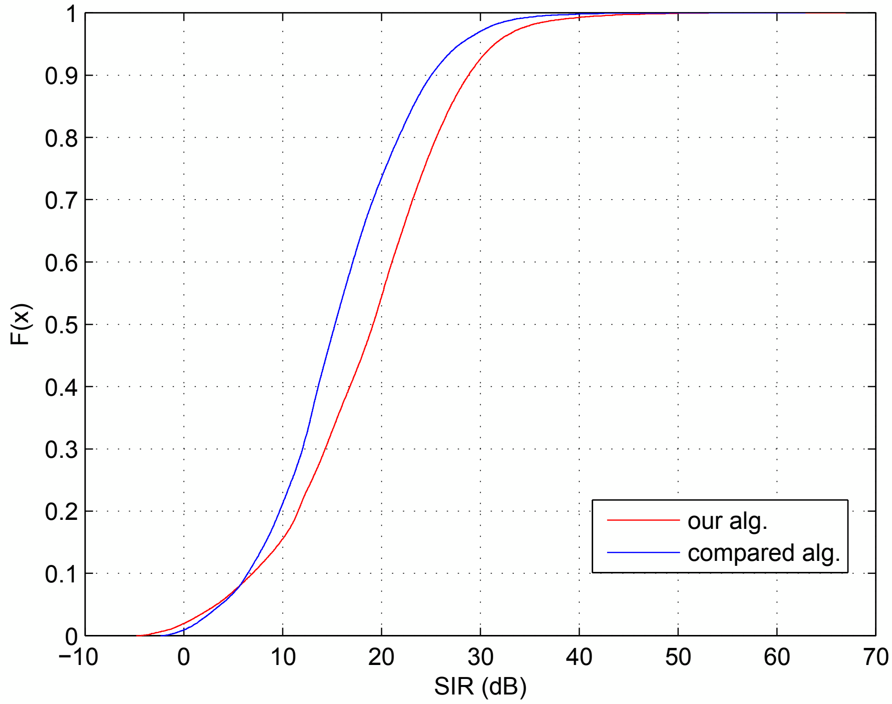

Figure 6.15: CDF comparison of SIR for InH experiments

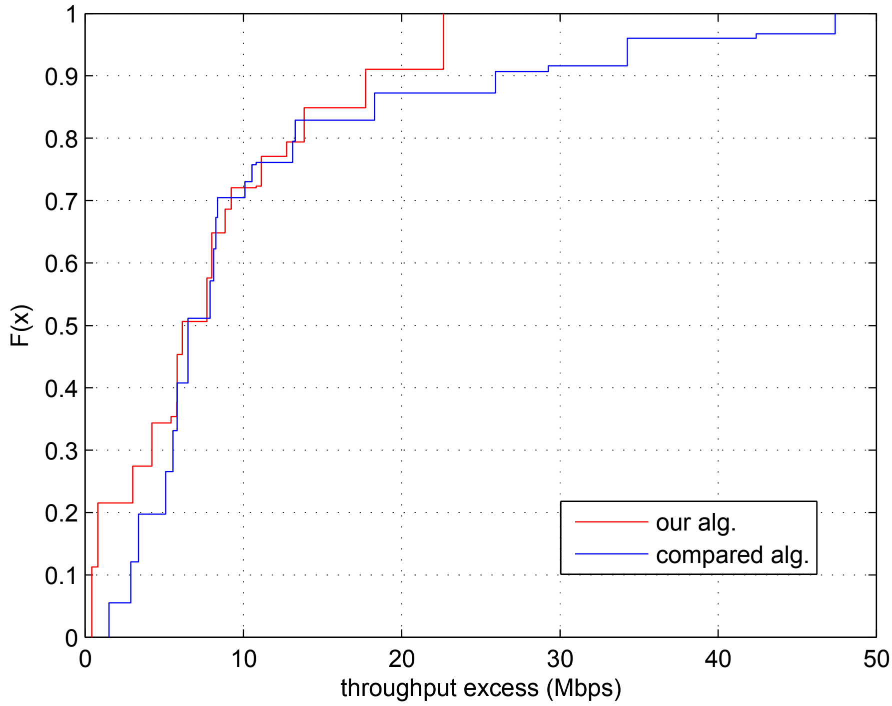

Figure 6.16: CDF comparison of throughput excess for InH experiments

6.2 Experiment for Real Building Scenario

6.2.1 Experiment Setup

We evaluate the planning platform for a more realistic scenario in this section. The system parameters for the real building scenario are listed in Table 6.2.

Table 6.2: System parameter for real building scenario

Map Size	150×300 points
Scale	3X (square grid = $0.\bar{3}$m × $0.\bar{3}$m)
Candidate station number	88
Wall number	183
Priority map area number	4
Path loss model	802.11n model D (Typical office)
AP signal power	21 dBm
Carrier frequency	2.4 GHz
Stream number	2
Bandwidth	40 MHz
Guard interval	400 ns
Receive sensitivity	-95 dB
Max needed receive power	-70 dB (MCS 15)
Min needed receive power	-95 dB (MCS 0)
Mean power difference threshold at min priority	20 dB
Mean power difference threshold at max priority	15 dB
Channel number	3

The floor map is the second electrical engineering building of National Taiwan University. The scale of the map is 3X, which means a point on the map is about a 0.3m-sided square grid. There are 88 candidate APs, and the topology map with candidate AP locations is presented in Figure 6.17. In the topology, the green lines are concrete wall, blue lines are drywalls and doors, and cyan lines are the elevator walls. The blue circles are the locations of candidate APs, and the heights of candidate APs are depicted by the number attached by the circles. The condition of the area priority is shown in Figure 6.18. The throughput constraint is illustrated in Figure 6.19. At last, the distribution of the people density is illustrated in Figure 6.20.

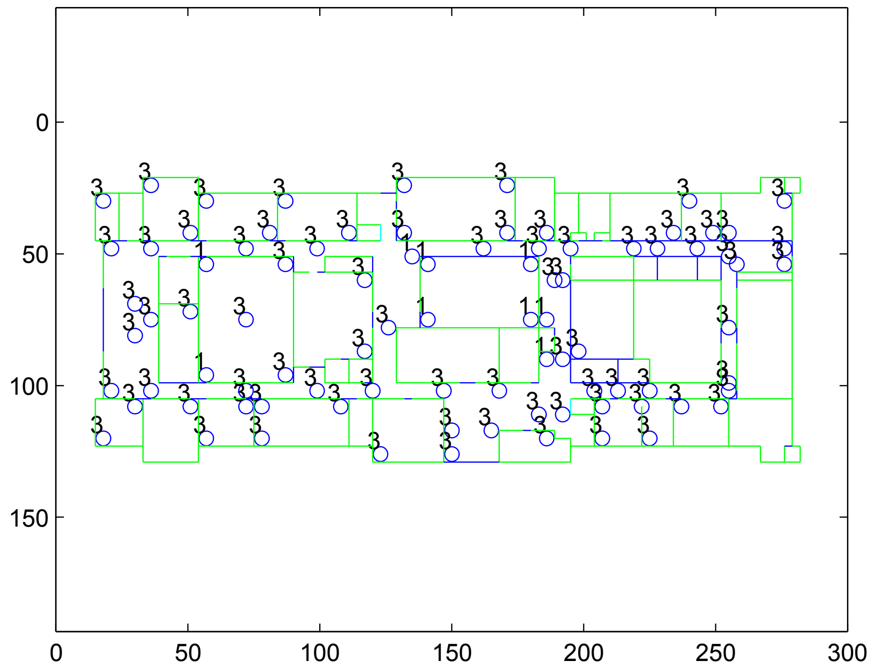

Figure 6.17: Topology map with candidate APs' information for real building scenario

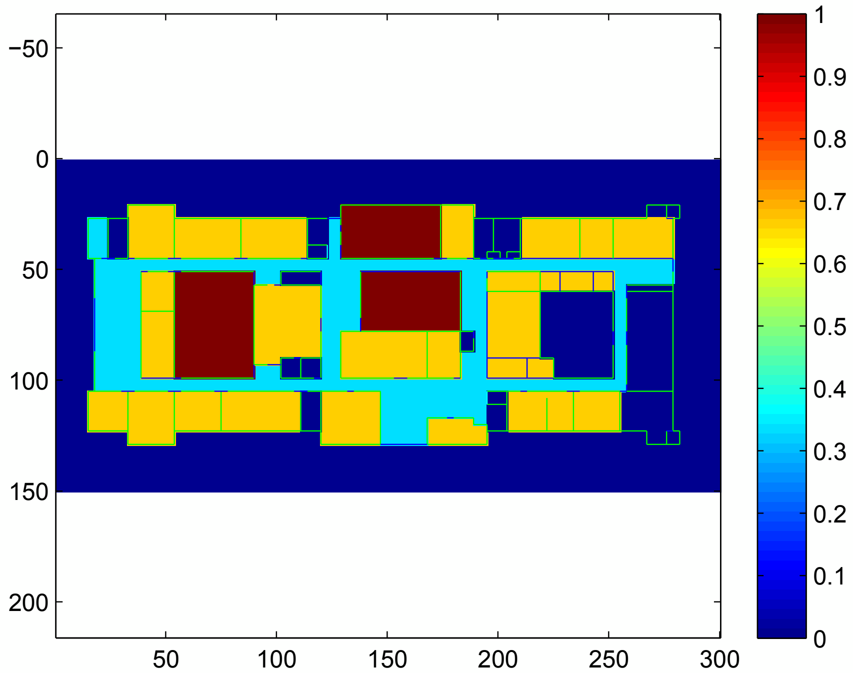

Figure 6.18: Priority map for real building scenario

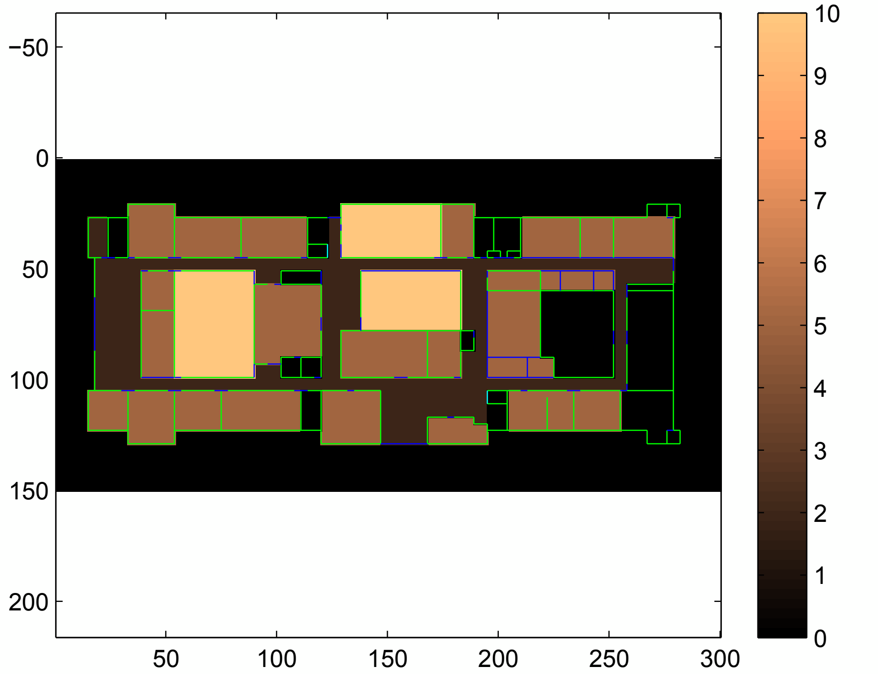

Figure 6.19: Throughput requirement map for real building scenario

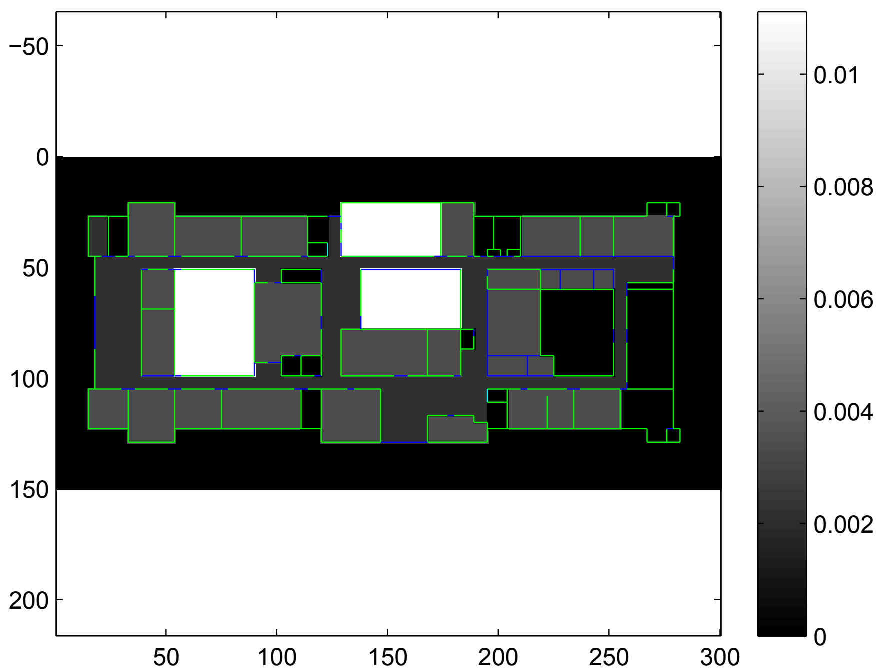

Figure 6.20: People density map for real building scenario

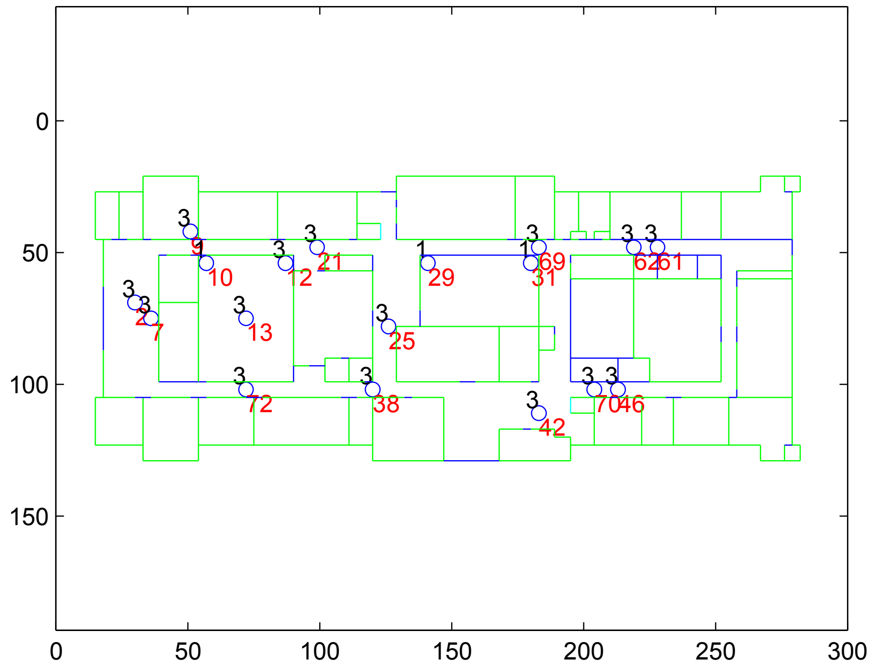

Figure 6.21: Selected APs for real building scenario

6.2.2 Result

The result of the experiment of real building scenario is demonstrated in this section. After the AP selection process, 18 APs are selected in this scenario and the resulted signal strength map is presented in Figure 6.22. The allocation of served area is depicted in Figure 6.23, and the channel allocation status is shown in Figure 6.24 with detail illustrated in Table 6.3. The received power algorithm wins by 36.0572 dB of averaged SIR, and the SIR distribution is shown in 6.25. The resulted throughput satisfies the requirement, and the throughput distribution for such deployment is shown in Figure 6.26. At last, the CDF of SIR and throughput excess in effective area is shown in Figure 6.27 and Figure 6.28 ,respectively.

Table 6.3: Carrier assignment result for real building scenario

Carrier index	AP index
1	7 10 12 25 29 46 61
2	13 38 42 69
3	2 9 21 31 62 70 72

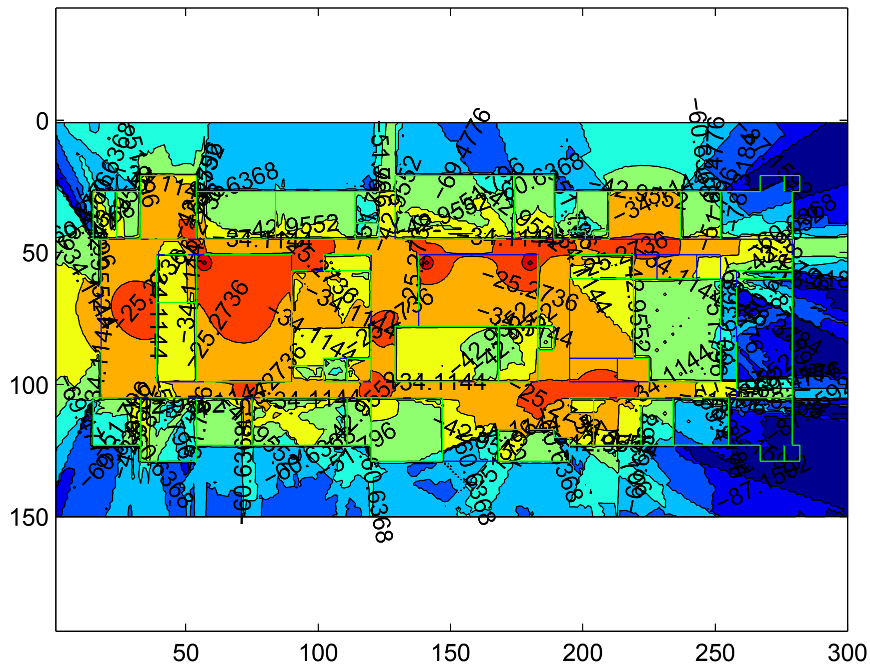

Figure 6.22: Signal strength contour map of selected APs for real building scenario

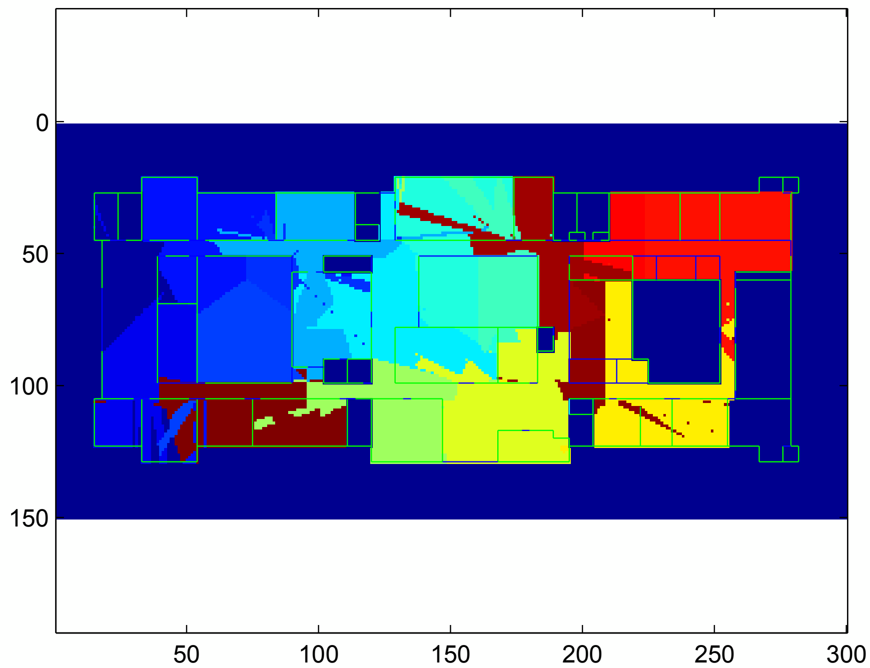

Figure 6.23: Allocation map of selected APs for real building scenario

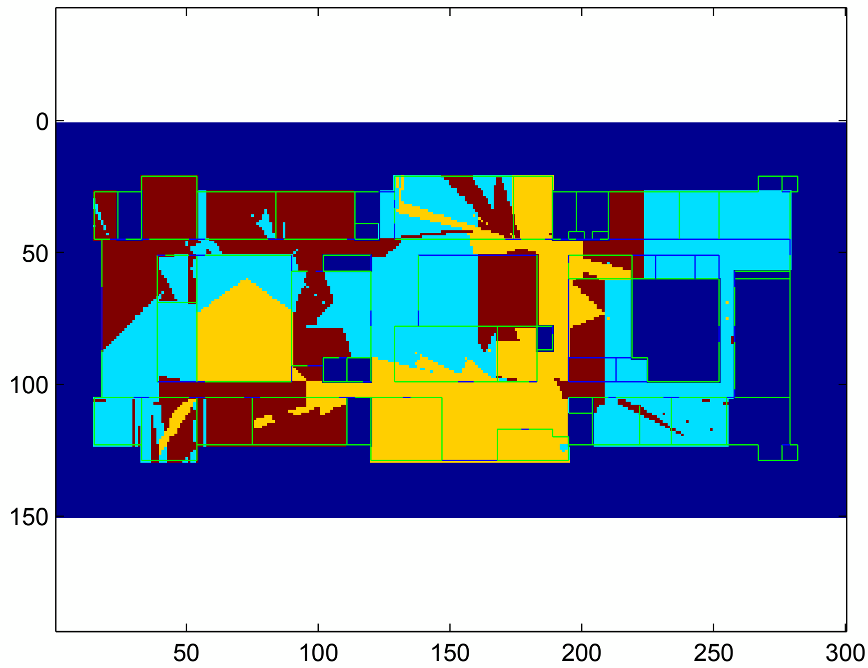

Figure 6.24: Channel allocation map of selected APs for real building scenario

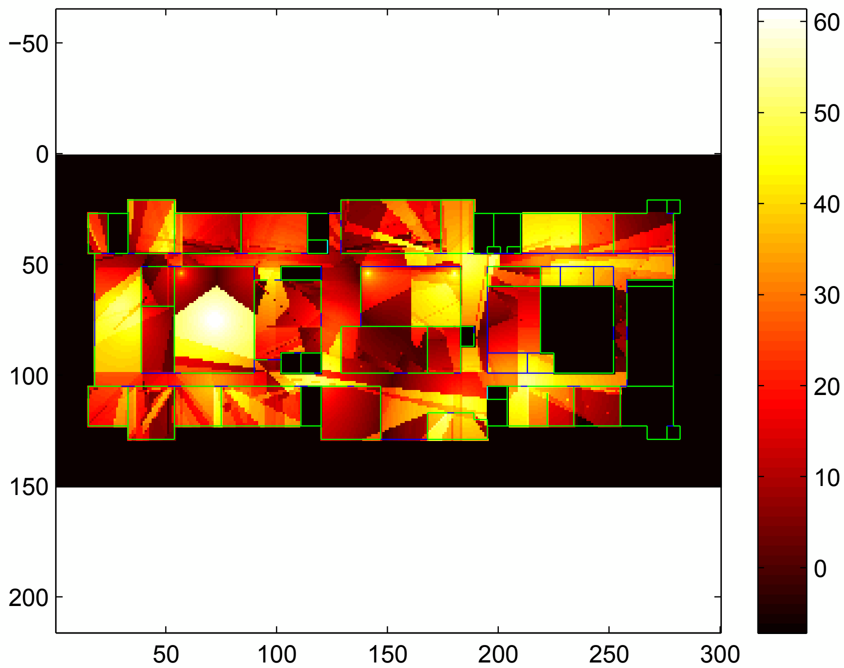

Figure 6.25: SIR map for real building scenario

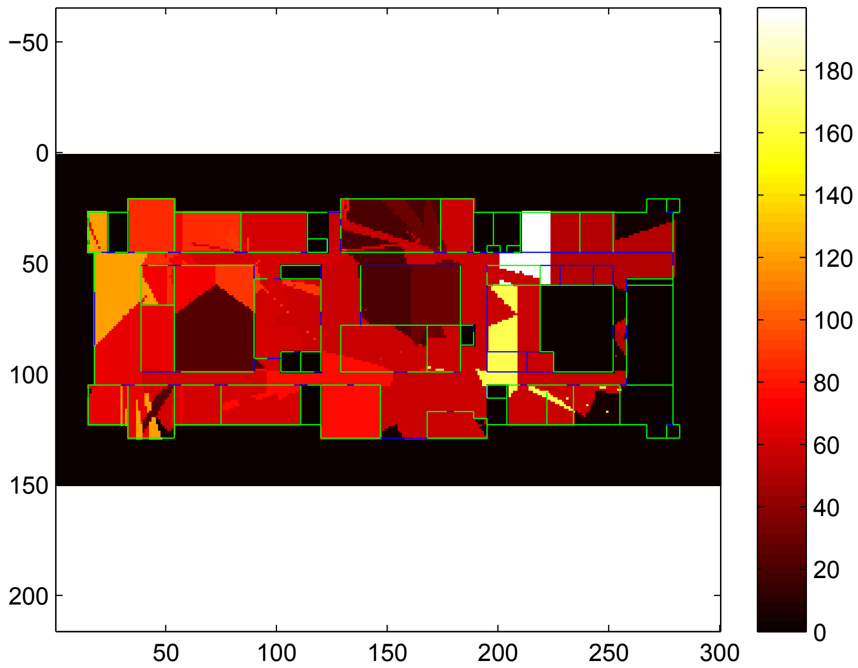

Figure 6.26: Theoretical throughput map for real building scenario

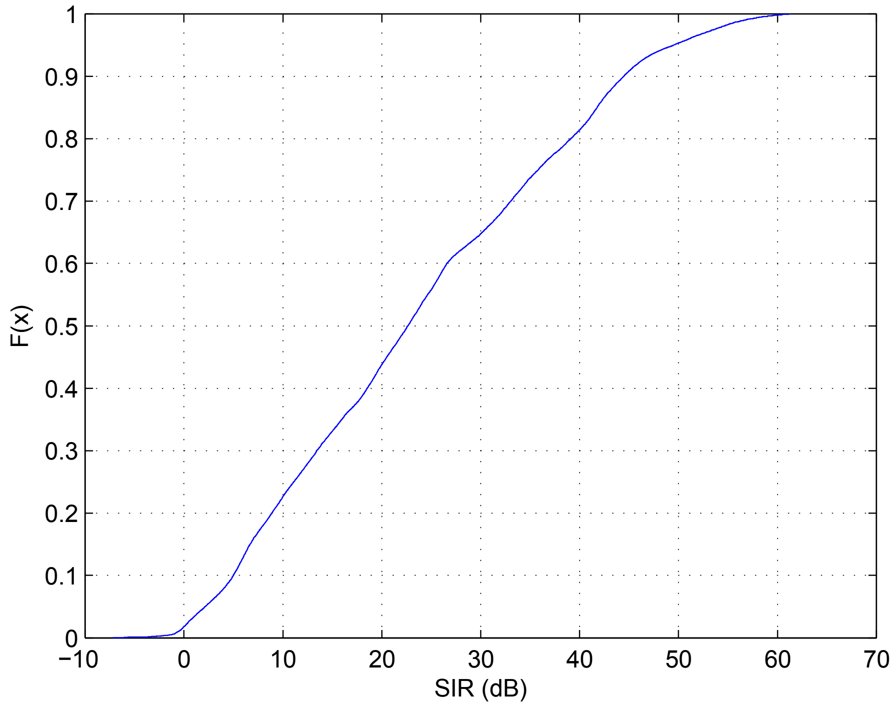

Figure 6.27: CDF of SIR for real building scenario

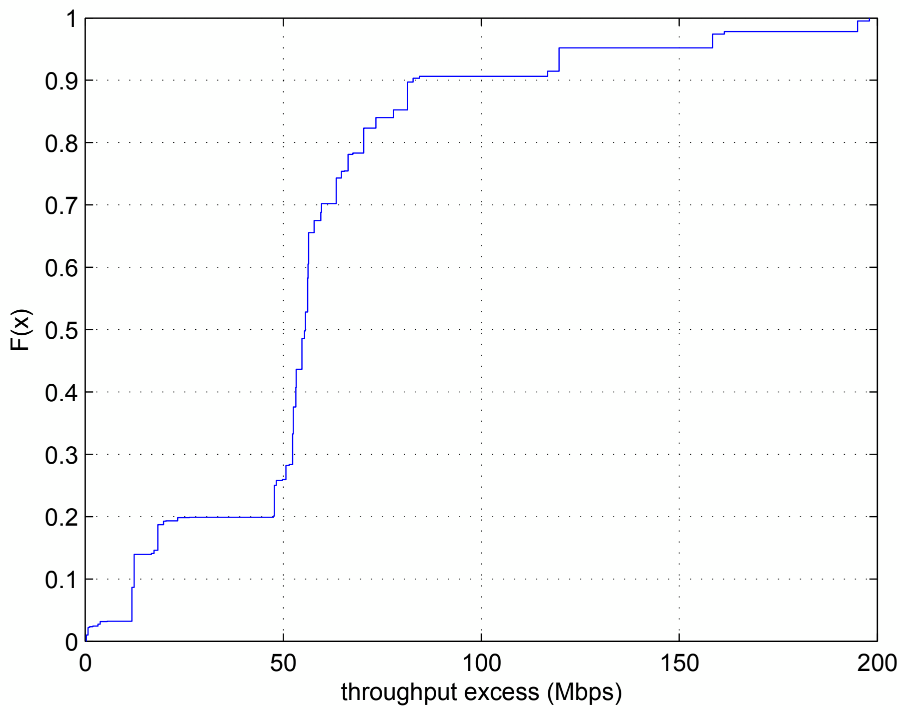

Figure 6.28: CDF of throughput excess for real building scenario

Chapter 7

Conclusion

We have implemented a WiFi network planning platform which mainly provides suggestion of AP selection and channel allocations for network deployment. The network planning platform contains three modules that are able to meet the designer's demand in different stages of network design: From the signal strength module, designers can compute the signal strength map over specified topology. From the AP selection module, they can derive an AP deployment plan that have better coverage, less interference, and sufficient throughput with a set of candidate APs. From the channel assignment module, a channel assignment plan for such deployment can be obtained.

We have discussed the design specification of our platform, and the optimization approach is accomplished in several stages. First, we propose an optimization model that estimates the throughput in a more accurate form, and use a heuristic approach to greedily find important APs which has more effective coverage from a predefined AP set. Next, we ensure the selected AP set to provide enough throughput that satisfy the requirement. At last, we utilize two channel assignment algorithms to minimize the co-channel interference as well as maximize the SIR over the whole area.

As our algorithm take the people density into consideration, the platform can also be applied to the planning of networks in public place where the amount of visitors varies with time. When there are fewer visitors, our algorithm can provide an AP selection plan that only turns on fewer APs to satisfy the traffic need, and thus save the operating cost of already deployed APs.

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