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Designing 802.11 wireless networks includes two major components: selection of access points (APs) in the demand areas and assignment of radio frequencies to each AP. Coverage and capacity are some key issues when placing APs in a demand area. APs need to cover all users. A user is considered covered if the power received from its corresponding AP is greater than a given threshold. Moreover, from a capacity standpoint, APs need to provide certain minimum bandwidth to users located in the coverage area.

A major challenge in designing wireless networks is the frequency assignment problem. The 802.11 wireless LANs operate in the unlicensed ISM frequency, and all APs share the same frequency. As a result, as 802.11 APs become widely deployed, they start to interfere with each other and degrade network throughput. In consequence, efficient assignment of channels becomes necessary to avoid and minimize interference.

In this work, we develop an optimal AP selection by balancing traffic load. We formulate an optimization problem that minimizes heavy congestion. As a result, APs in wireless LANs will have well distributed traffic loads, which maximize the throughput of the network. We design our channel assignment algorithm by minimizing channel interference between APs. Our optimization algorithm assigns channels in such a way that minimizes co-channel and adjacent channel interference resulting in higher throughput.

OPTIMAL ACCESS POINT SELECTION AND CHANNEL ASSIGNMENT IN IEEE 802.11 NETWORKS

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CHAPTER 1

INTRODUCTION

People are going wireless. The high cost and sometimes impossible task of running cables for building wired network infrastructures contribute to rapid wireless network development on a global scale. One approach is to equip facilities with access points and devices with short-range radio transmitters and receivers to allow them to communicate. The market for wireless network communications has accelerated after the IEEE introduced the 802.11 wireless local area network (LAN) standards [7].

802.11 wireless networks offer performance nearly comparable to that of Ethernet [1]. In addition, they provide scalability and relative ease of integrating wireless access. Wireless LANs support user demand for seamless connectivity, flexibility, and mobility [23]. The most prominent differences between wireless LANs and wired LANs are transmission medium and speed. Since wireless networks send radio frequencies through the air, channels should be assigned to each access point such that interferences between adjacent cells and between co-channel cells are minimized [8].

1.1 IEEE 802.11 Overview

The IEEE 802 committee began the task on wireless LANs in 1987 within the IEEE 802.4 group. The original work was developing wireless communication in the unlicensed industrial, scientific, and medical (ISM) bands at 915 MHz, 2.4 GHz, and 5 GHz using a token-passing bus medium access control (MAC) protocol. However, they concluded that token bus was not suitable to control a radio medium because of inefficient use of the radio spectrum. As a result, the IEEE 802 formed a new working group in 1990, the IEEE 802.11

for wireless LANs to develop a MAC protocol and physical medium specification [22].

In 1997, the IEEE 802.11 committee came up with a standard where the data rates were 1 Mbps and 2 Mbps [10]. In 1999, a split development within the committee resulted in two standards, the 802.11a and the 802.11b [11, 12]. The 802.11a standard uses orthogonal frequency division multiplexing [3] and a higher frequency band (5 GHz), and it offers data rates up to 54 Mbps. The 802.11b standard uses the same frequency band as the original 802.11 (2.4 GHz) and high range direct sequence spread to achieve 11 Mbps. In 2003, the 802.11 committee approved a new 802.11g standard [13], which uses the modulation technique of 802.11a and the frequency range of 802.11b.

Designing 802.11 wireless networks includes two major components: placement of access points in the demand areas and assignment of radio frequencies to each access point [15]. Coverage and capacity are some key issues when placing access points in a demand area [21]. Access points need to cover all users. A user is considered covered if the power received from its corresponding access point is greater than a given threshold. Moreover, from a capacity standpoint, access points need to provide certain minimum bandwidth to users located in the coverage area.

A major challenge in designing wireless networks is the frequency assignment problem [15]. The 802.11 wireless LANs operate in the unlicensed ISM frequency, and all access points share the same frequency. As a result, as 802.11 access points become widely deployed, they start to interfere with each other and degrade network throughput [2]. Efficient assignment of channels becomes necessary to avoid and minimize interference. There are two types of interference in wireless networks: adjacent channel interference and co-channel interference. Adjacent channel interference occurs between access points that are adjacent to each other. On the other hand, co-channel interference occurs between access points which use the same channels.

1.2 Objectives

In this work, we develop an optimal access point selection by balancing traffic load. In addition, we investigate the effect of minimizing channel interferences by assigning optimal channels to the access points.

The objectives of this work are as follows:

- **Optimal Access Point Selection and Traffic Allocation:**
  - Formulation of an optimal access point placement by balancing traffic load.
- **Optimal Channel Assignment:**
  - Formulation of an optimal channel assignment by minimizing interference between access points in 802.11b wireless LANs.

1.3 Organization

In Chapter 2, we investigate the protocol stack, physical layer, and the MAC sublayer protocol of the IEEE 802.11 standards. All access points and stations share the same transmission medium. To avoid frame collision, the MAC protocol coordinates access to the medium with carrier sense multiple access with collision avoidance technique. Interference and collision degrade network throughput, so intelligent access point selection and optimal channel assignment become paramount procedures when deploying 802.11 wireless networks.

In Chapter 3, we design our access point placement algorithm by balancing traffic load. We formulate an optimization problem that minimizes heavy congestion. As a result, access points in wireless LANs will have well distributed traffic loads, which maximizes the throughput of the network.

In Chapter 4, we design our channel assignment algorithm by minimizing channel interference between access points. Assigning non-overlapping co-channels to access points is a crucial process for overall performance. Our optimization algorithm assigns channels in a way that minimizes co-channel and adjacent channel interference resulting in higher throughput.

Finally, in Chapter 5, we present our conclusions and summarize the contributions of this work.

CHAPTER 2

THE 802.11 MAC SUBLAYER PROTOCOL

2.1 Introduction

The 802.11 medium access control (MAC) sublayer protocol provides a contention free and a contention based access control on a variety of physical mediums. It provides an effective and distributed mechanism to coordinate the medium access among access points (AP) and stations. We will investigate the physical layer of the 802.11 standard and explain the details of the MAC sublayer protocol.

2.2 The 802.11 Protocol Stack

All the 802.11 protocols have analogous structures in terms of the Open Systems Interconnection (OSI) model [24]. The physical layer corresponds to the OSI physical layer, but the data link layer splits into two sublayers as shown in Fig. 2.1. In 802.11, the MAC sublayer determines how the channel is allocated. Above it is the logical link control (LLC) sublayer, whose job is to hide the differences between the 802.11 variants and make them indistinguishable to higher layers. The separation of layers is necessary in wireless LANs because the logic required to manage a shared-access medium is not found in a traditional data link layer.

2.3 The 802.11 Physical Layer

In 1997, the 802.11 standard specified three transmission techniques allowed in the physical layer: infrared, frequency hopping spread spectrum (FHSS), and direct sequence spread

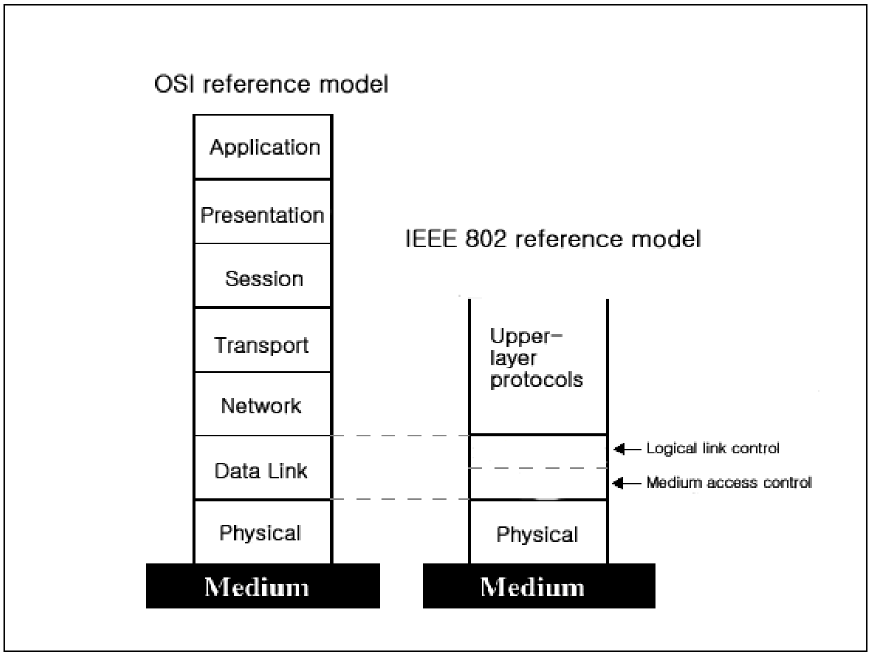

Figure 2.1: The 802.11 protocol stack architecture compared to the OSI model.

spectrum (DSSS) as shown in Fig. 2.2 [22]. The infrared method uses the same technology as television remote controls. It uses a diffused transmission, not a line of sight. Infrared signals cannot penetrate walls, so rooms equipped with infrared wireless LANs are isolated from each other. This is not a popular option because of its low data rate (1 Mbps or 2 Mbps) and the fact that sunlight wipes out infrared signals.

The other two 802.11 methods, exploiting FHSS and DSSS techniques, use short-range radio operating in the unlicensed industrial, scientific, and medical (ISM) bands at 2.4 GHz. FHSS uses 1 MHz bandwidth with 79 channels, which begins at the low end of the 2.4 GHz ISM band (2.412 GHz in U.S.). A pseudorandom number generator produces the sequence of frequencies hopped to. As long as all stations use the same seed to the pseudorandom number generator and stay synchronized in time, they will hop to the same frequencies simultaneously. It provides a good security since a user who does not know the hopping sequence or dwell time, the amount of time spent at each frequency, cannot eavesdrop. The main disadvantage of FHSS is the low data rate (1 Mbps or 2 Mbps). DSSS also transmits

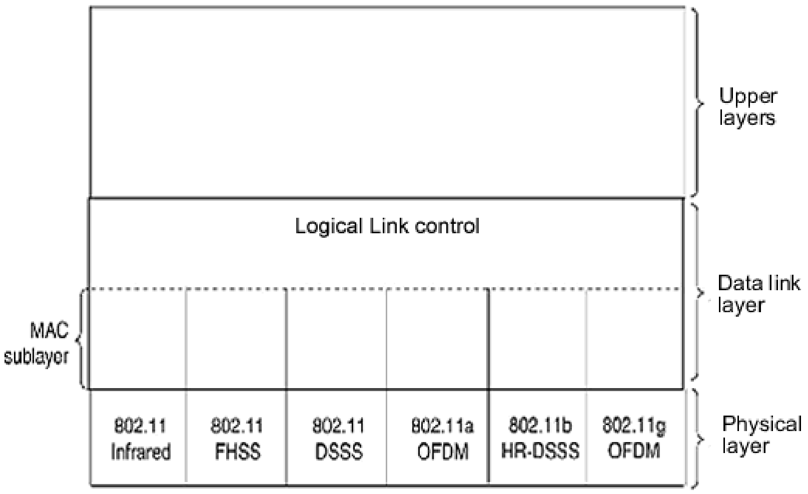

Figure 2.2: Lower layers of the 802.11 protocol stack.

at 1 Mbps or 2 Mbps. In DSSS, each bit is transmitted as 11 chips, called a Barker sequence. It uses phase shift modulation at 1 Mbaud that transmits 1 bit per baud when operating at 1 Mbps and 2 bits per baud when operating at 2 Mbps.

In 1999, two new techniques, 802.11a and 802.11b, were introduced for higher data rates [11, 12]. They use orthogonal frequency division multiplexing (OFDM) and high range direct sequence spread spectrum (HR-DSSS), respectively. 802.11a operates at up to 54 Mbps in the higher 5 GHz ISM band. 52 different frequencies are used in 802.11a, 48 for data and 4 for synchronization. OFDM splits the signal into many narrow bands, so the transmissions are present on multiple frequencies at the same time. Some key advantages of splitting the signal into many narrow bands instead of using a single wide band are efficient use of spectrum and a better immunity to narrow band interference [3, 6].

802.11b uses HR-DSSS, which uses 11 million chips per second to achieve 11 Mbps in the 2.4 GHz ISM band. 802.11b is not a descendant of 802.11a. In fact, the IEEE approved the 802.11b standard first, and it got to market first. Since it operates at the same frequency as the previous 802.11 standard and supports the data rates of 1, 2, 5.5 and 11 Mbps, 802.11b is compatible with prior 802.11 specifications. Although 802.11b is slower than 802.11a, its range is about 7 times farther because it uses 2.4 GHz. The 2.4 GHz band is divided into 11 channels, but to limit interference between channels, 802.11b will use less than half of these in transmission.

In 2003, a new 802.11g standard was approved [13]. It uses the OFDM modulation of 802.11a but operates in the narrow 2.4 GHz band of 802.11b. 802.11g supports data rates up to 54 Mbps. Since 802.11g is backward compatible with 802.11b, it has become a good choice for users to adopt because it does not require an upgrade to client equipment and offers speeds comparable to 802.11a.

2.4 The 802.11 MAC Sublayer Protocol

The IEEE 802.11 MAC sublayer protocol is similar to wired Ethernet. They both listen to the mediums before they start transmission. However, wireless LANs present some unique challenges that do not exist in wired Ethernet.

For instance, a computer always listens before it starts transmitting in Ethernet to find whether the network is idle [20]. With wireless networks, that method does not work very well because of the radio transmitter range limit. An access point can hear both computers A and B, but neither A nor B can hear each other as shown in Fig. 2.3. This might create a situation in which the AP can be receiving a transmission from B without A sensing that node B is transmitting. Since A senses no activity on the channel, it may also begin transmitting which will interfere with the access point's reception of B's transmission. This is known as hidden node problem.

Also, multipath fading of radio signals is a challenge. Multipath is a phenomenon whereby radio signals travel more than one route between the transmitter and receiver. As a result, radio signals may arrive multiple times at the receiver. In addition, stations cannot monitor

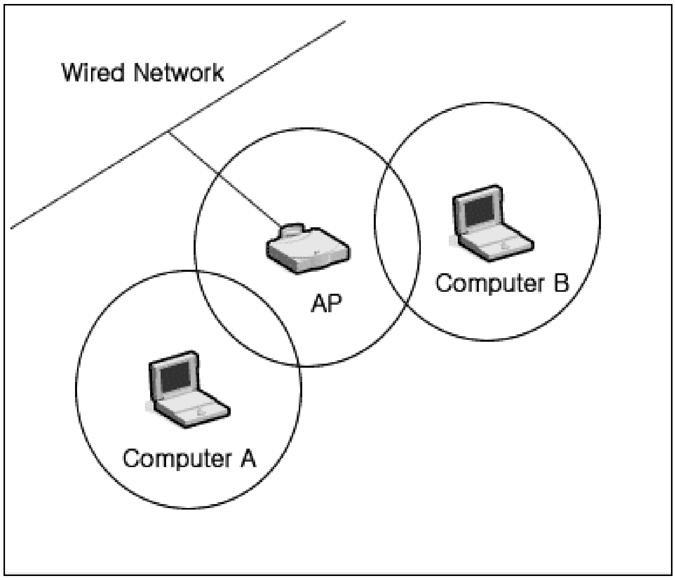

Figure 2.3: Hidden node problem in wireless LANs.

the wireless medium while transmitting. The IEEE 802.11 MAC protocol is designed to meet these unique challenges.

The 802.11 MAC protocol supports two types of operations: distributed coordination function (DCF) and point coordination function (PCF) as shown in Fig. 2.4. DCF uses carrier sense multiple access with collision avoidance (CSMA/CA) for contention-based access. On the other hand, PCF uses contention-free access, which uses the AP to control all activity in its cell. Two modes are used alternately in time.

DCF uses CSMA/CA algorithm with binary exponential backoff. A station with a frame to transmit competes for the medium by first sensing the medium and delaying transmission until it is idle for a minimum period of time. If the medium is idle, a station starts transmission. If the frame is received without error, the destination station returns a positive acknowledgment frame. If the originating station does not receive the positive acknowledgment frame, the station assumes that an error has occurred, and it delays transmission for a backoff interval. The interval is doubled for every frame error experienced until the preset maximum interval is reached. After a random backoff interval has been satisfied, the trans-

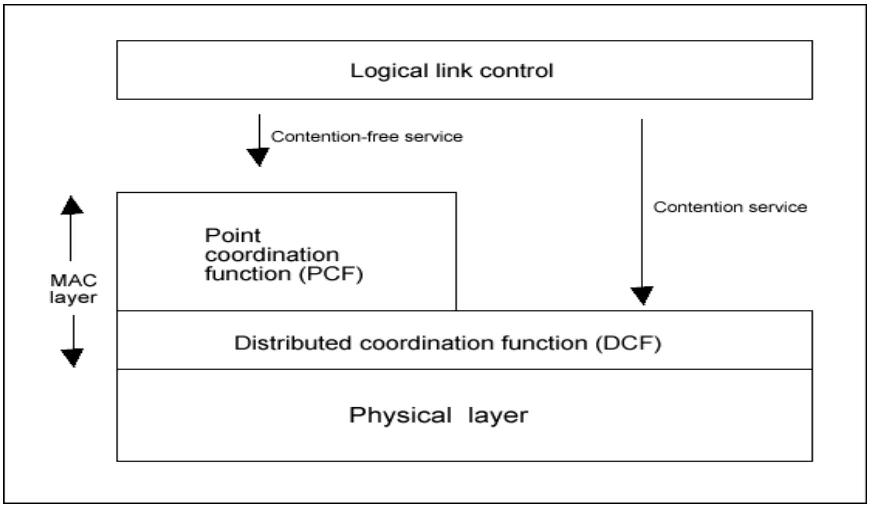

Figure 2.4: IEEE 802.11 MAC layer architecture.

mitting station contends for the medium again. The binary exponential backoff provides a way for handling heavy load because failed transmission results in longer and longer backoff times, thus it helps to smooth out the load.

In addition to the medium sensing, the 802.11 MAC protocol implements a network allocation vector (NAV), which informs each station about the amount of time that remains before the medium will be idle. All packets contain a duration field, and the NAV is updated according to the duration field value in each decoded frame. The NAV is thus referred to as a virtual carrier sensing mechanism. The 802.11 MAC uses both CSMA/CA and virtual carrier sensing to avoid collision. Moreover, the 802.11 MAC has a four-way protocol. It requires the transmitter and receiver exchange the Request-to-Send (RTS) and Clear-to-Send (CTS) frames before sending data.

The protocol starts when a station A decides to send a frame to a station B as shown in Fig. 2.5. First, station A sends an RTS frame to station B to request permission to send it a frame. When station B receives the request, it sends a CTS frame back if it grants the permission. Upon arrival of the CTS, station A now sends its data frame and starts an Acknowledgment (ACK) waiting timer. Upon correct receipt of the data frame, station B

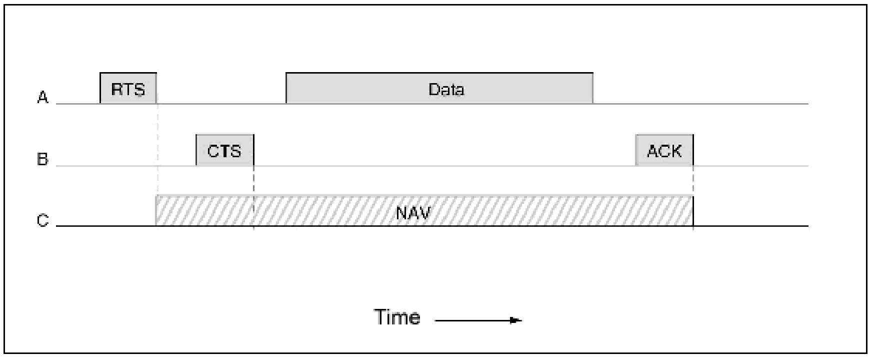

Figure 2.5: The virtual sensing mechanism.

responds with an ACK frame, terminating the exchange. If station A's ACK waiting timer expires before the ACK arrives, the whole process repeats again.

A station C, within range of A, may receive the RTS frame also, and it realizes that someone is going to send data soon. Not to interfere with that exchange, it forbids anything to transmit until that communication is completed. Station C can always estimate how long the exchange will take because it was provided in the RTS request, so it sets a virtual channel busy for itself indicated by NAV.

In addition to DCF, the IEEE 802.11 offers PCF, a contention-free access method. PCF is an alternative medium access method implemented on top of the DCF. In PCF, the AP polls the other stations, asking them if they have any frames to send. No collisions will ever occur since the AP in PCF mode controls all transmissions and broadcasts a beacon frame periodically. The beacon frame contains system parameters, such as clock synchronization. It also invites new stations for polling services. Once a new station has signed up for services at a certain rate, it is guaranteed a certain bandwidth.

DCF and PCF can exist together within one cell. The 802.11 provides carefully defined interframe time intervals. After a frame has been sent, a certain amount of dead time is required before any station may send a frame. Four different intervals are defined for specific purposes as shown in Fig. 2.6.

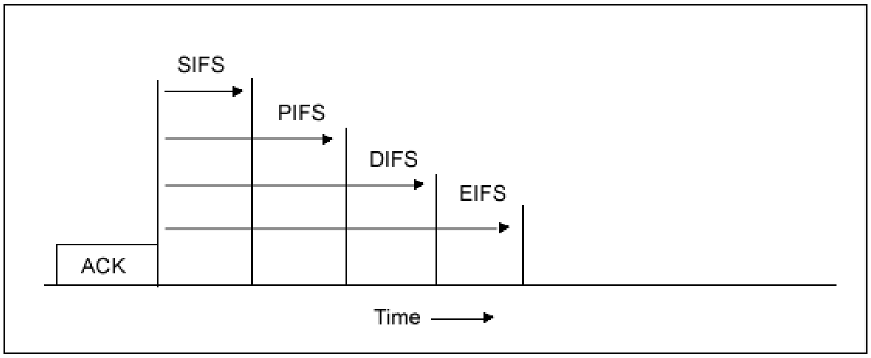

Figure 2.6: The four different interframe intervals.

The shortest interval is the short interframe space (SIFS). SIFS is used between certain multiframe exchange sequences, such as acknowledgment frame sent in response to the error free reception of a frame. After a SIFS interval, only one station is eligible to respond. If a station fails to respond and a PCF interframe (PIFS) interval expires, the AP may send a beacon frame to poll services. If the AP has been idle and a DCF interframe space (DIFS) elapses, any station may compete to acquire the medium to send a new frame. The binary exponential back off is needed if a collision occurs. Extended interframe space (EIFS) is used to manage the reception of a bad or unknown frame.

2.5 Summary

We examined the protocol stack, physical layer, and the MAC sublayer protocol of the IEEE 802.11 wireless LANs standards. The transmission medium is shared by all access points and stations. To avoid frame collision, the MAC protocol coordinates access to the medium with CSMA/CA technique along with NAV. Interference and collision degrade network throughput, so intelligent AP selection and optimal channel assignment become paramount procedures when deploying the 802.11 wireless LANs.

CHAPTER 3

OPTIMAL ACCESS POINT SELECTION AND TRAFFIC ALLOCATION

3.1 Introduction

Designing 802.11 wireless networks includes two major components: placement of access points (AP) in the service areas and assignment of radio frequencies to each AP. Coverage and capacity are some key issues when placing APs in a service area. APs need to cover all users. A user is considered covered if the power received from its corresponding AP is greater than a given threshold. Moreover, from a capacity standpoint, APs need to provide certain minimum bandwidth to users located in the coverage area. In this chapter, we present our design procedures for 802.11 wireless LANs and our AP selection and traffic allocation algorithm to optimally balance the traffic load.

3.2 Related Work

In [5], the authors use a divide-and-conquer algorithm to select APs. The algorithm divides the total service area into equally sized squares. The problem is then solved in each of these divisions by exhaustive search.

In [15], the authors formulate an integer linear programming problem for optimizing AP placement. The algorithm maximizes the throughput by considering load balancing among APs. The optimization objective is to minimize the maximum of channel utilization of the hot spot service area.

In [17], the authors formulate different optimization problems with various objective functions. The considered variables are positions of APs, their heights, their transmission power levels, and antenna sectorization. The optimization problems maximize the number of covered demand nodes while penalizing multiple coverage of demand nodes.

In [21], the authors use techniques for placement of base stations in an outdoor environment for building an indoor wireless network. The algorithm minimizes the number of APs, that cover a desired service area.

In [25], the authors use a greedy algorithm to solve the AP placement problem. The algorithm begins with a set of potential locations for APs. In each iteration, a new AP is greedily picked from the set that covers the maximum number of uncovered demand nodes. This algorithm assumes that if an AP covers the most demand nodes, it is more desirable to select it.

3.3 Design Procedure

APs should be placed so that there are no coverage gaps in the service areas. In addition, the coverage overlap among APs should be minimized to avoid interference and achieve better throughput. If too many APs are used, the cost of equipment and installation will be higher than necessary.

Some important issues when placing APs are coverage of service areas and throughput requirements. Our approach for designing 802.11 wireless LANs is composed of the following steps:

1. Creation of a service area map: A service area map will be divided into smaller demand clusters where the number of users or traffic requirements of each demand cluster is given. An example of a service area map for a three story building with 60 demand clusters is given in Fig. 3.1.

2. Creation of a signal level map: A signal level map is either measured or estimated using a radio propagation model. Signal levels at demand clusters should be greater than a

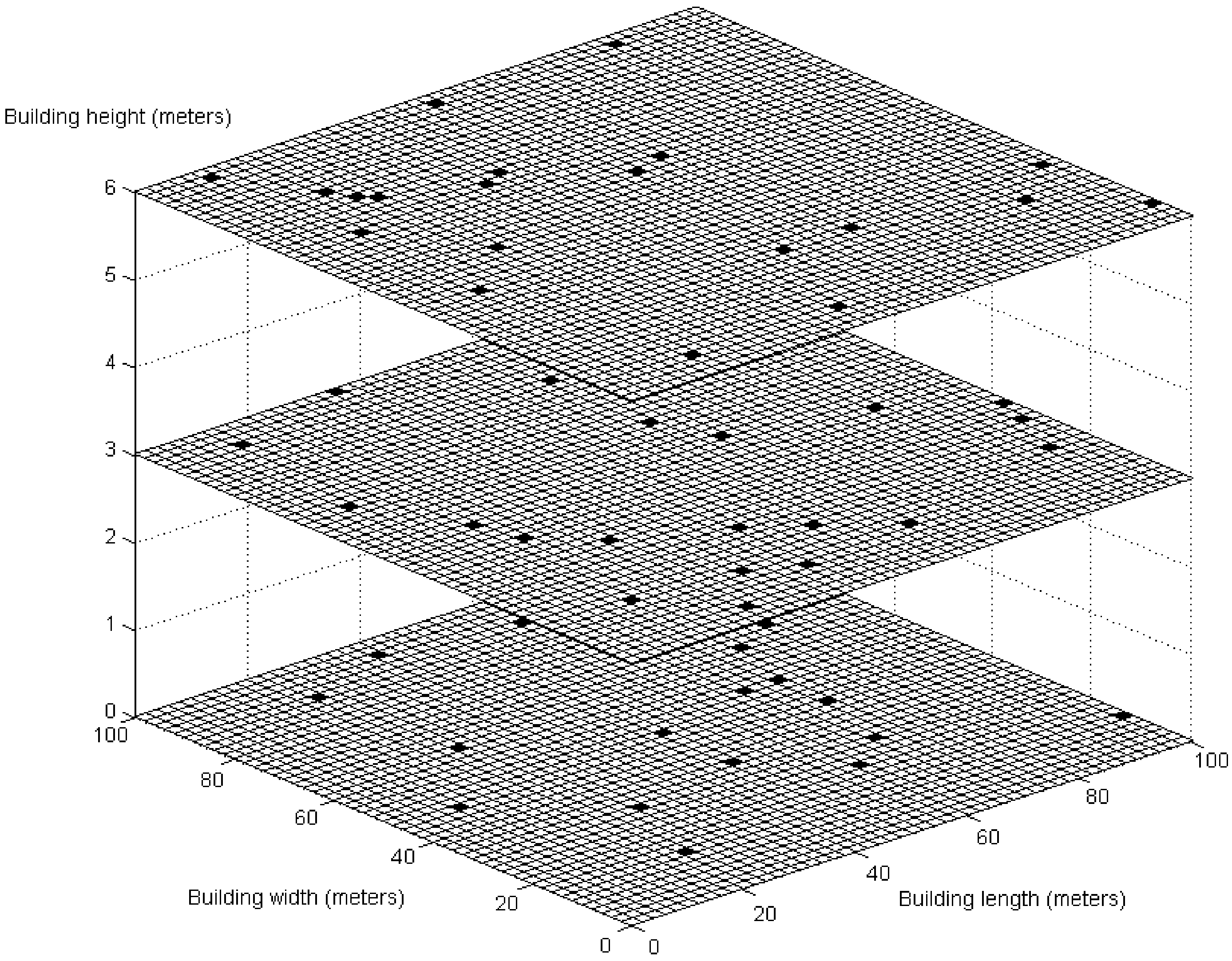

Figure 3.1: A service area map for a three story building with 60 demand clusters.

given threshold in order to provide an adequate signal-to-noise ratio. An example of a signal level map for a three story building with 14 APs is given in Fig. 3.2.

3. Placement of candidate APs: Candidate APs must be placed taking into account the connection to the wired LANs, power supply needs, and installation costs.

4. Selection of the APs from among a set of candidate locations: Using the service area map and the signal level map, we can calculate the best locations of APs from among possible candidate locations to satisfy traffic demands and capacity requests. Balancing traffic loads will be crucial to avoid and minimize bottleneck APs, which increases network throughput.

5. Assignment of frequencies to APs: After AP locations have been finalized, frequencies are assigned to the APs so that co-channel interference and adjacent channel interference are minimized. This process will be covered in the next chapter.

3.4 Optimal Access Point Selection and Traffic Allocation

3.4.1 Assumptions

The following assumptions are made to aid in the placement problem.

- L is the total number of demand clusters. Demand clusters are defined as the locations of high traffic loads in the service area.
- M is the total number of candidate APs. The APs are chosen such that every demand cluster must be connected to at least one candidate AP.
- S_{ij} is the signal level at demand cluster i of AP j.
- D_i is the location of a demand cluster i.

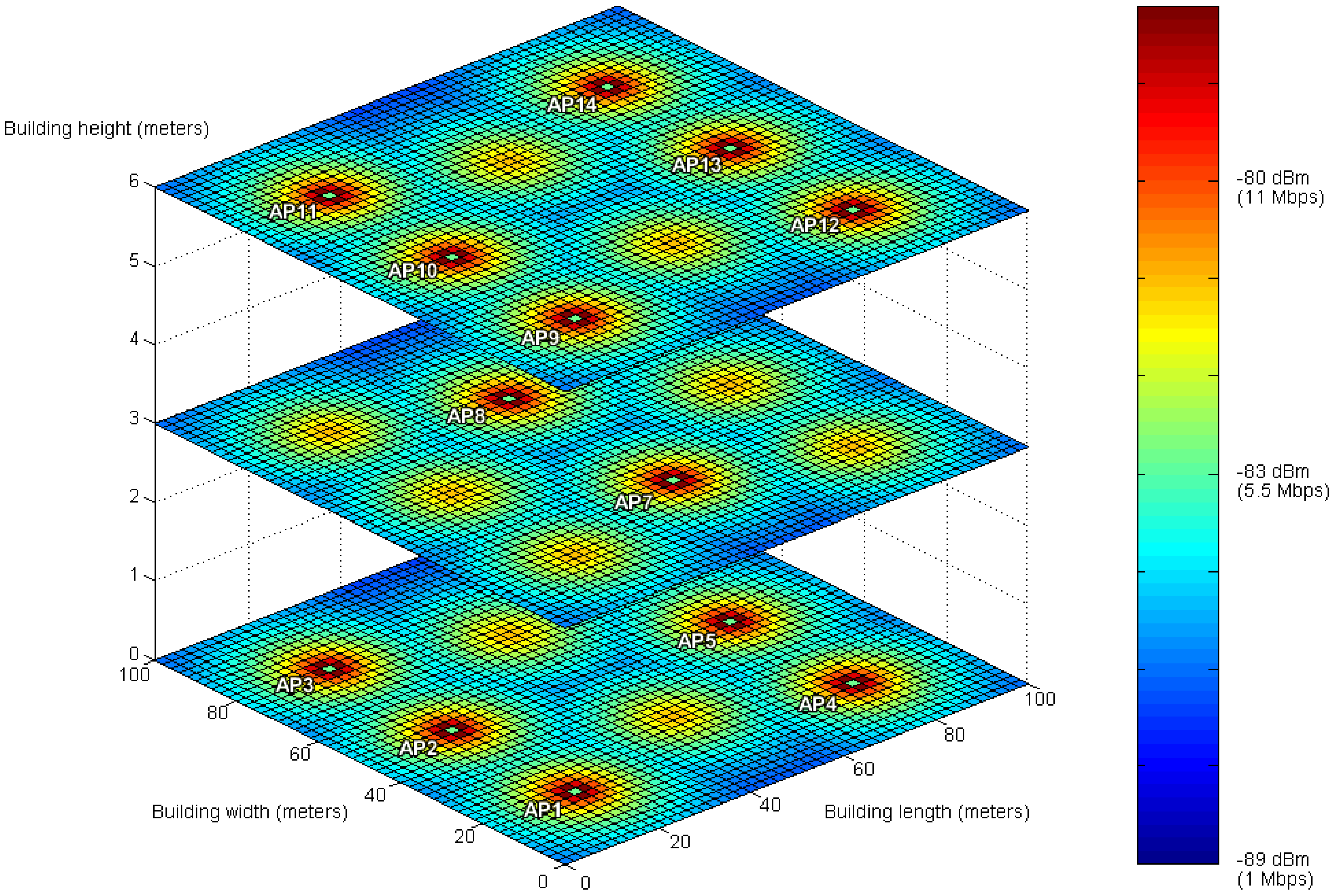

Figure 3.2: A signal level map for a three story building with 14 APs.

- T_i is the average traffic load of demand cluster i. Traffic requests from a demand cluster i will be assigned to only one AP.

- Candidate AP assignment graph, $G = (N, E)$:
  - Nodes (N) consist of a set of demand cluster and a set of candidate APs.
  - Edge (E) exists between a demand cluster i, D_i, and a candidate AP j if the signal level, S_{ij}, is greater than a given threshold.

3.4.2 The Optimization Problem

Load balancing is crucial when APs are chosen because distributing user traffic demands to APs results in higher throughput. We formulate the problem of AP selection and traffic allocation by minimizing the congestion of the most heavily loaded APs. By minimizing the bottleneck APs, we can get better bandwidth utilization for the whole network, which will result in higher throughput.

We formulate an integer optimization problem [4]. The following variables are defined.

- x_{ij} is a binary variable that is 1 when demand cluster i is assigned to AP j and 0 otherwise.

- B_i is the maximum bandwidth of AP i.

- C_i is the congestion factor of AP i.

The optimal AP selection and traffic allocation problem is given as follows:

$$\min_{x_{ij},\quad 1 \leq i \leq L,\quad 1 \leq j \leq M,} \qquad \max\{C_1, C_2, ..., C_M\}, \quad (1)$$

$$\text{subject to} \qquad \sum_{i=1}^{L} x_{ij} \leq 1, \quad (2)$$

$$C_j = \frac{1}{B_j}\sum_{i=1}^{L} T_i \cdot x_{ij}, \quad (3)$$
$$\text{for} \quad j = 1, ..., M. \tag{3.1}$$

Objective (1) minimizes the maximum congestion of chosen APs. Constraint (2) states that each demand cluster should be assigned to only one AP. Constraint (3) defines the congestion factor of the APs. The solution to the above optimization problem yields the number of APs that are selected from the candidate APs. If $C_i = 0$ for an AP i, then AP i is not selected.

3.5 Numerical Results

We used LINGO [14] to solve the integer optimization problem. The service area is a three story building with 100 meter length and 100 meter width.

First, we created a service area map with 20 demand clusters, and we generated a signal level map of 14 candidate APs. The service area map with the signal level map for the three story building is shown in Fig. 3.3.

The number of users per demand cluster is uniformly distributed between 1 and 10. The average traffic demand per user is assumed to be 200 Kbps, and each AP provides a maximum bandwidth of 11 Mbps in 802.11b. The average traffic load of a demand cluster i, T_i, can be calculated as the number of users at demand cluster i multiplied by the average traffic demand per user. The average traffic load used in the analysis is given in Table 3.1.

We generated a candidate AP assignment graph from our service area map and signal level map. As shown in Table 3.2, a demand cluster i, D_i, may be connected to multiple APs if the signal level, S_{ij}, of an AP j at D_i is greater than a given threshold, which we set to -80 dBm. For instance, D_2 is connected to AP 2 and AP 3 while D_1 is connected to AP 6 only. Also, demand clusters, D_8 through D_{13} located on the second floor, are connected to more APs than demand clusters located on other floors since ample signals can be received

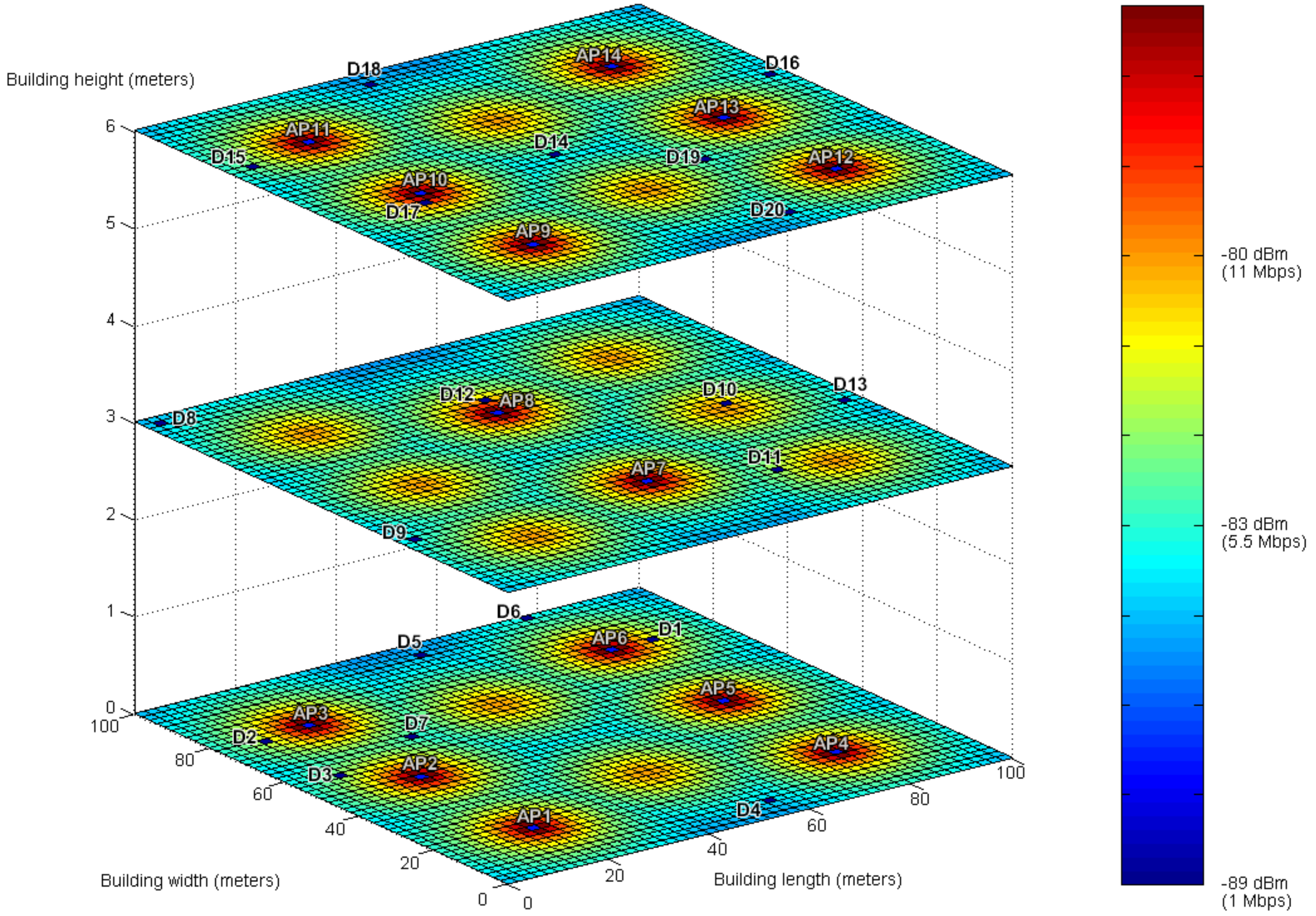

Figure 3.3: The signal level map for a three story building with 14 APs and 20 demand clusters.

Table 3.1: The average traffic load, T_i (Kbps), at demand cluster i.

T_1	1,600	T_{11}	1,400
T_2	2,000	T_{12}	2,000
T_3	800	T_{13}	1,800
T_4	1,800	T_{14}	400
T_5	1,200	T_{15}	400
T_6	400	T_{16}	2,000
T_7	800	T_{17}	200
T_8	400	T_{18}	800
T_9	1,800	T_{19}	800
T_{10}	1,600	T_{20}	400

from both the first and third floors.

The results of our optimization showed that our algorithm selected all APs among the candidate APs, as given in Table 3.3. This table confirms that each demand cluster is assigned to only one AP which is the first constraint of our optimization problem. Our analysis also yielded that the congestion of APs is distributed throughout the network to avoid bottleneck APs, as given in Table 3.4. The congestion factor, C_i, would be zero if AP i is not selected by our optimization algorithm.

The AP selection derived from Table 3.3 is shown in Fig. 3.4. The demand cluster 17, D_{17}, selected AP 9 instead of AP 10, which is closer, since AP 10 already has been selected by D_{14} and D_{15}. By having D_{17} select AP 9, it reduces the congestion at AP 10 while it still receives ample service from AP 9. D_{15} selected AP 10 instead of AP 11, which is closer, since D_{18}, which has double the traffic demand of D_{15}, selected AP 11. Therefore, D_{15} selecting AP 10, reduces the congestion at AP 11.

As has been demonstrated in our analysis, a demand cluster will not necessarily select the closest AP that has the largest signal level. Our optimization balances the load on the

Table 3.2: A candidate AP assignment graph with 14 APs and 20 demand clusters. An edge exists between D_i and AP j if the value is 1. A demand cluster may be connected to multiple APs if it is within the signal level threshold.

E	AP_1	AP_2	AP_3	AP_4	AP_5	AP_6	AP_7	AP_8	AP_9	AP_{10}	AP_{11}	AP_{12}	AP_{13}	AP_{14}
D_1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
D_2	0	1	1	0	0	0	0	0	0	0	0	0	0	0
D_3	0	1	1	0	0	0	0	0	0	0	0	0	0	0
D_4	0	0	0	1	0	0	1	0	0	0	0	0	0	0
D_5	0	0	0	0	0	0	0	1	0	0	0	0	0	0
D_6	0	0	0	0	0	1	0	0	0	0	0	0	0	0
D_7	0	1	1	0	0	0	0	1	0	0	0	0	0	0
D_8	0	0	1	0	0	0	0	0	0	0	1	0	0	0
D_9	1	1	0	0	0	0	0	0	1	1	0	0	0	0
D_{10}	0	0	0	0	1	1	0	0	0	0	0	0	1	1
D_{11}	0	0	0	1	0	0	1	0	0	0	0	1	0	0
D_{12}	0	0	0	0	0	1	0	1	0	0	0	0	0	1
D_{13}	0	0	0	1	1	0	0	0	0	0	0	1	1	0
D_{14}	0	0	0	0	0	0	1	1	0	1	0	0	0	0
D_{15}	0	0	0	0	0	0	0	0	0	1	1	0	0	0
D_{16}	0	0	0	0	0	0	0	0	0	0	0	0	1	1
D_{17}	0	0	0	0	0	0	0	0	1	1	0	0	0	0
D_{18}	0	0	0	0	0	0	0	1	0	0	1	0	0	0
D_{19}	0	0	0	0	0	0	1	0	0	0	0	1	1	0
D_{20}	0	0	0	0	0	0	1	0	0	0	0	1	0	0

Table 3.3: The solution to our optimization problem yields the following values for x_{ij}. Every demand cluster is assigned to only one AP.

x_{ij}	AP_1	AP_2	AP_3	AP_4	AP_5	AP_6	AP_7	AP_8	AP_9	AP_{10}	AP_{11}	AP_{12}	AP_{13}	AP_{14}
D_1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
D_2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
D_3	0	1	0	0	0	0	0	0	0	0	0	0	0	0
D_4	0	0	0	0	0	0	1	0	0	0	0	0	0	0
D_5	0	0	0	0	0	0	0	1	0	0	0	0	0	0
D_6	0	0	0	0	0	1	0	0	0	0	0	0	0	0
D_7	0	1	0	0	0	0	0	0	0	0	0	0	0	0
D_8	0	0	1	0	0	0	0	0	0	0	0	0	0	0
D_9	1	0	0	0	0	0	0	0	0	0	0	0	0	0
D_{10}	0	0	0	0	1	0	0	0	0	0	0	0	0	0
D_{11}	0	0	0	1	0	0	0	0	0	0	0	0	0	0
D_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	1
D_{13}	0	0	0	0	0	0	0	0	0	0	0	1	0	0
D_{14}	0	0	0	0	0	0	0	0	0	1	0	0	0	0
D_{15}	0	0	0	0	0	0	0	0	0	1	0	0	0	0
D_{16}	0	0	0	0	0	0	0	0	0	0	0	0	1	0
D_{17}	0	0	0	0	0	0	0	0	1	0	0	0	0	0
D_{18}	0	0	0	0	0	0	0	0	0	0	1	0	0	0
D_{19}	0	0	0	0	0	0	1	0	0	0	0	0	0	0
D_{20}	0	0	0	0	0	0	0	0	0	0	0	1	0	0

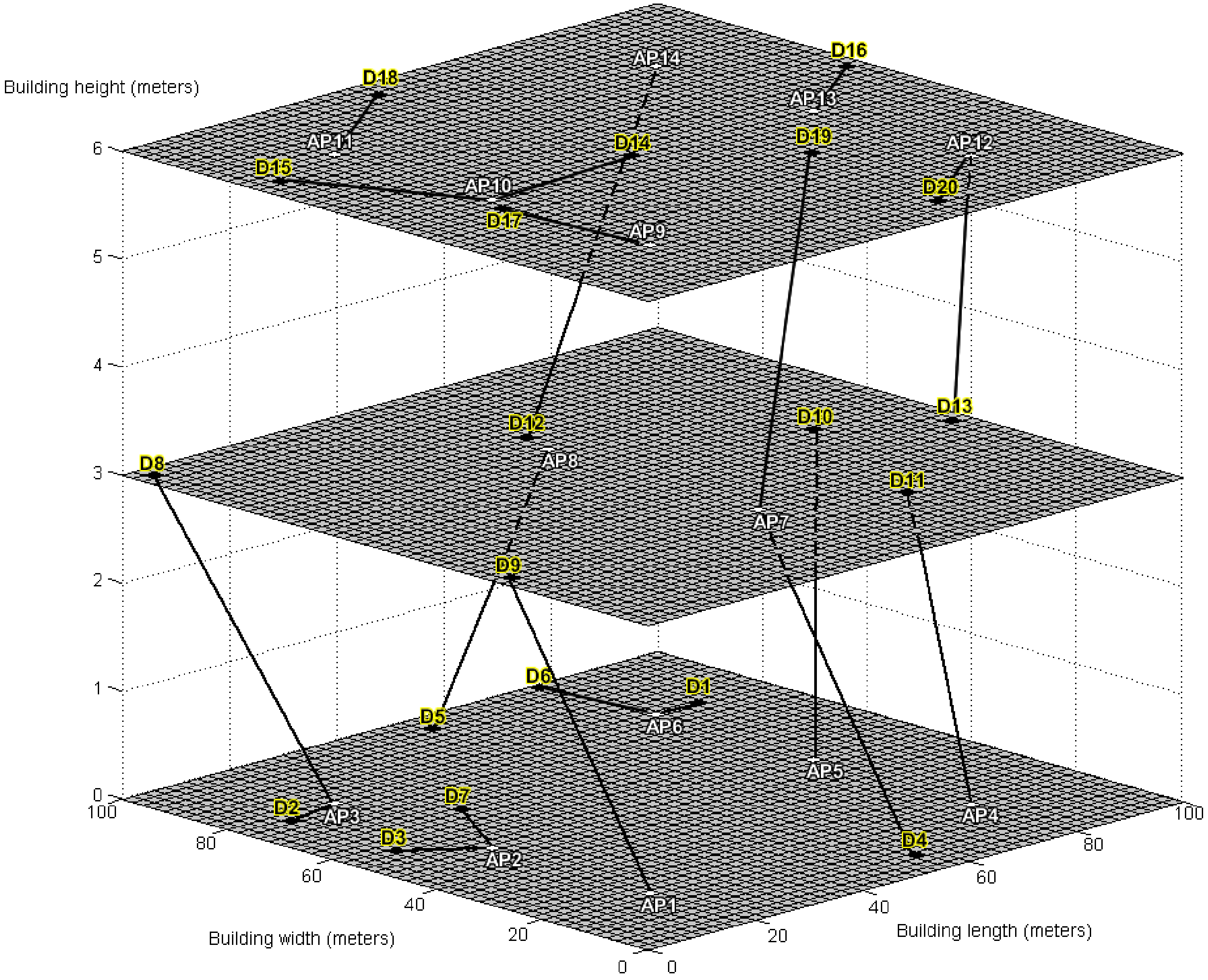

Figure 3.4: AP selection with 14 APs and 20 demand clusters.

Table 3.4: Congestion factor, C_i, of the 14 APs.

C_1	0.164	C_8	0.109
C_2	0.145	C_9	0.018
C_3	0.218	C_{10}	0.073
C_4	0.127	C_{11}	0.073
C_5	0.145	C_{12}	0.2
C_6	0.182	C_{13}	0.182
C_7	0.236	C_{14}	0.182

entire network such that demand clusters might select APs which have slightly lower signal levels but still can service the demand clusters and provide ample bandwidth.

We randomly generated the locations of 15, 20, 25, and 30 demand clusters in our three story building. The results are given in Fig. 3.5. The congestion factor, C_i, increases, as expected, as the number of demand clusters increases. However, the load remains balanced across the networks. Fig. 3.6 shows the average congestion across the network as we vary the number of APs and the number of demand clusters.

3.6 Summary

We proposed an optimal AP selection and traffic allocation algorithm by formulating a constrained optimization problem. By minimizing heavy congestion, APs in WLANs will have well distributed traffic loads. We analyzed a three story building with 14 APs and 20 demand clusters. A demand cluster will not necessarily select the closest AP that has the largest signal level. Our optimization balances the load on the entire network such that demand clusters might select APs which have slightly lower signal levels but still can service the demand clusters and provide ample bandwidth. Our results also confirmed that when the number of demand clusters increases, the congestion factor of APs is also increased; the

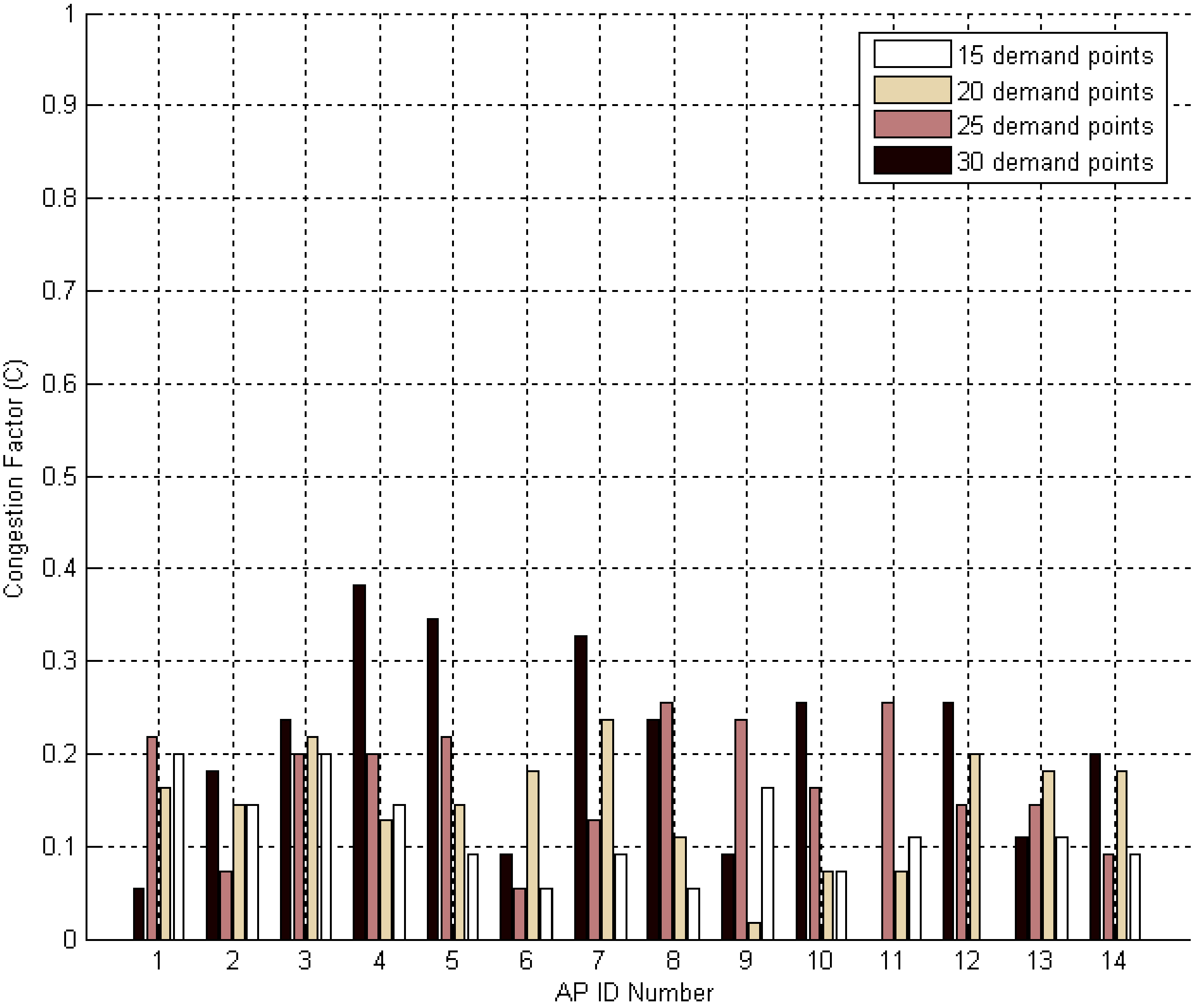

Figure 3.5: Congestion factor of 14 APs with 15, 20, 25, and 30 demand clusters.

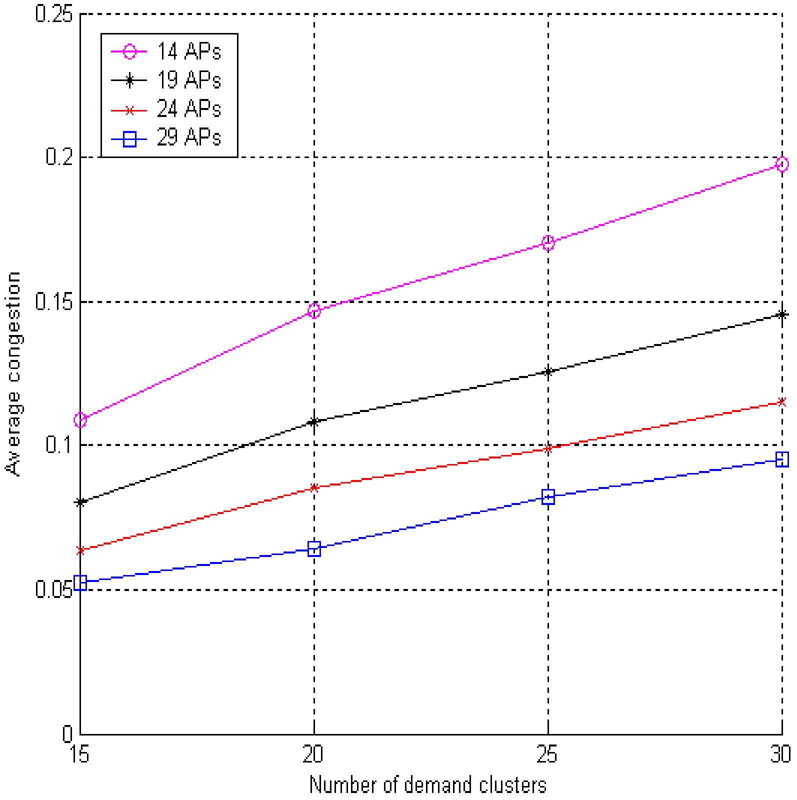

Figure 3.6: Average congestion across the network decreases as the number of APs is increased.

congestion factor decreases when more APs are added.

CHAPTER 4

OPTIMAL CHANNEL ASSIGNMENT

4.1 Introduction

After the access point (AP) locations have been finalized, frequencies are assigned to the selected APs. For example, in North America, the ISM band at 2.4 GHz is divided into 11 channels for the 802.11b wireless LANs. In principle, all 11 channels are available. However, overlapping co-channels and adjacent channels between APs cause interference and degrade throughput. Consequently, assigning non-overlapping co-channels to APs is a crucial process for overall performance. Frequencies should be assigned in such a way that minimizes co-channel and adjacent channel interference.

4.2 Related Work

In [8], the authors propose a method that exhaustively checks the co-channel overlap for all possible frequency assignments. The authors also use the wireless LAN coverage map so that co-channel APs have minimum coverage overlaps.

In [9], the authors use an algorithm that has an exponential computational complexity to assign frequencies to APs. The algorithm generates an optimal frequency assignment to APs that has minimal co-channel overlap but is computationally intensive. Therefore, the authors also use a greedy algorithm that is close to optimal but may not yield the optimal frequency assignment for a given wireless LAN.

In [16], the authors formulate the channel assignment problem by considering the network traffic load at the MAC layer and prove that the problem is NP-complete. The authors

Table 4.1: Frequency and channel assignments.

CHANNEL	FREQUENCY	CHANNEL	FREQUENCY
1	2.412GHz	8	2.447GHz
2	2.417GHz	9	2.452GHz
3	2.422GHz	10	2.457GHz
4	2.427GHz	11	2.462GHz
5	2.432GHz	12	2.467GHz
6	2.437GHz	13	2.472GHz
7	2.442GHz	14	2.484GHz

propose a heuristic algorithm to analyze it.

In [18], the authors experiment with radio interference between channels for 802.11b. The experiments show that a channel separation of either 3 or 4 between APs is suitable.

4.3 Channel Interference

802.11b networks operate between 2.4 GHz and 2.5 GHz. In 802.11b, transmissions between APs and stations do not use a single frequency. Instead, the frequencies are divided into 14 channels, and it uses a modulation technique, direct sequence spread spectrum, to spread the transmission over multiple channels for effective uses of frequency spectrum. In the United States, channels 1-11 are used. Europe uses channels 1-13. France uses channels 10-13, and Japan uses channels 1-14 as shown in Table 4.1. In this table, the channel represents the center frequency, and there is 5 MHz separation between the channels. 802.11b signal occupies approximately 30 MHz of the frequency spectrum. As a result, an 802.11b signal overlaps with several adjacent channel frequencies.

We can think of the signal overlaps with adjacent channels as people's conversations at a party at home with eleven different rooms [19]. In each of the eleven rooms, people are having different conversations. People in room one can hear the conversation of rooms one, two, three, four, and five. People in room six can hear the conversation of rooms two through ten, but they cannot hear anything from rooms one and eleven. People in room eleven can hear the conversation of rooms seven, eight, nine, ten, and eleven, so if people are only in room one, six, and eleven, they can have conversations without any noise coming from the other rooms.

Likewise, there are only three non-overlapping channels available in 802.11b, which are channels 1, 6 and 11 as shown in Fig. 4.1. Channel 1 overlaps with channel 2 through channel 5, and channel 6 overlaps with channel 2 through channel 10. Channel 11 overlaps with channel 7 through channel 10.

Channels should be assigned to APs such that co-channel interference is minimized. Channels are reused because of limited availability. The same channel could be assigned to two APs, which are located far enough apart, if the co-channel interference signal detected by each AP is less than a given threshold.

Use of overlapping channels degrades network throughput. Interference in 802.11 causes APs and stations to send frames over and over again to increase the odds of successful transmission. Typically, if devices were to send one copy of a frame, data is transmitted at 11 Mbps. However, if the efficiency were to drop to 50%, for instance, because of interference, the devices would still be transmitting at 11 Mbps, but it would be duplicating each frame, making the effective throughput 5.5 Mbps. Therefore, 802.11 networks will have a significant decrease in network performance because of interference.

We define the co-channel interference factor, w_{ij}, to be the relative percentage gain in interference as a result of two APs i and j using overlapping channels. Thus overlapping channels assigned to APs must be chosen carefully. For instance, if channel 1 is assigned to AP i and channel 1 is also assigned to AP j, the co-channel interference factor between AP i and AP j, w_{ij}, is 100%. If channel 5 is assigned to AP j, w_{ij} is 20%. If channels 6 or higher is assigned to AP j and higher, w_{ij} is 0%, which means there is no interference between AP

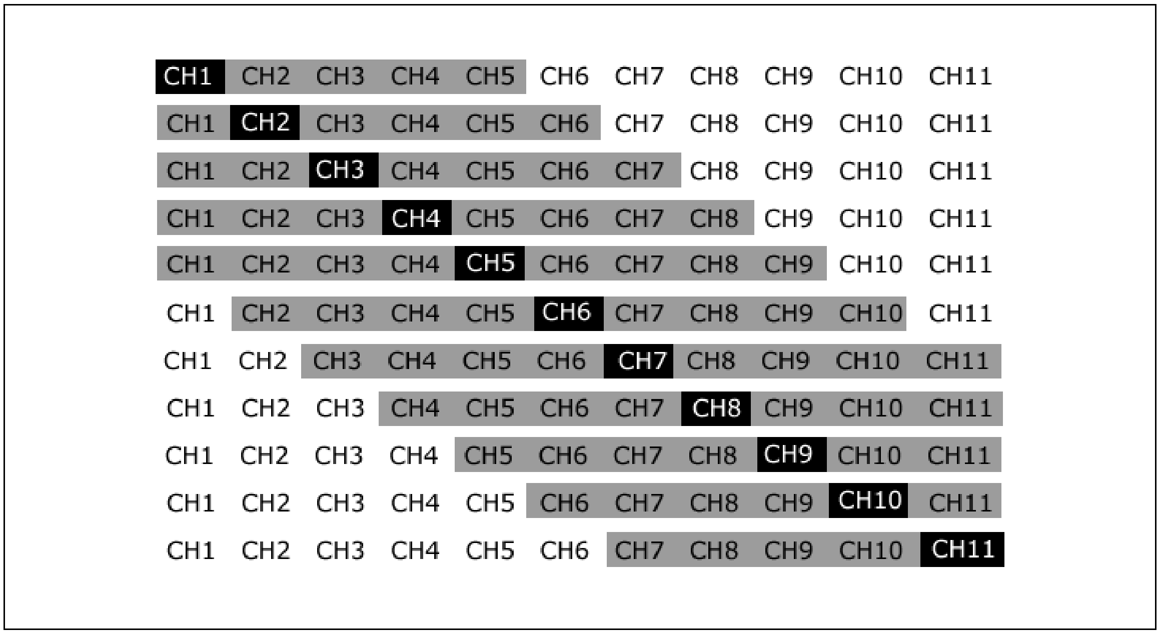

Figure 4.1: 802.11b channel overlap.

i and AP j.

4.4 Optimal Channel Assignment

Channels should be assigned to each AP in such a way that minimizes interference between APs. There are two types of interference in wireless LANs: adjacent channel interference and co-channel interference. Adjacent channel interference occurs between APs that are adjacent to each other. It is inversely proportional to the distance between the APs, which means the closer the APs, the higher the interference. On the other hand, co-channel interference occurs between APs that use overlapping channels. It is directly proportional to the co-channel interference factor. The closer the overlapping frequencies, the higher the interference.

We formulate our optimization problem using the following variables:

- K is the total number of available channels. 802.11b and 802.11g have 11 channels.

- F_i is the channel assigned to AP i. F_i belongs to the set of available channels.
- N is the total number of selected APs.
- V_i is the total interference at AP i.
- I_{ij} is the relative interference that AP j causes on AP i.
- w_{ij} is the co-channel interference factor between AP i and AP j.
- d_{ij} is the distance between AP i and AP j.
- m is a pathloss exponent.
- c is the overlapping channel factor. For instance, in 802.11b, c is 1/5 where 5 is the minimum number of overlapping channels.

The optimal channel assignment problem is given as follows:

$$\begin{aligned}
\min_{(F_1,F_2,\ldots,F_N)} \quad & \max\{V_1, V_2, \ldots, V_N\}, \quad (1) \\
\text{subject to} \quad & V_i = \sum_{j=1}^{N} I_{ij}, \quad (2) \\
& I_{ij} = \frac{w_{ij}}{d_{ij}^m}, \quad (3) \\
& w_{ij} = \begin{cases} 1 - |F_i - F_j| \times c & \text{if } w_{ij} \geq 0, \\ 0 & \text{otherwise,} \end{cases} \quad (4) \\
& \text{for} \quad i, j = 1, \ldots, N, \\
& \text{for} \quad F_i \in \{1, \ldots, K\}.
\end{aligned} \tag{4.1}$$

Objective (1) minimizes the maximum total interference at each AP. Constraint (2) defines the total interference at each AP. Constraint (3) defines the relative interference between AP i and AP j. Constraint (4) defines the co-channel interference factor between AP i and AP j, which have been assigned channels F_i and F_j, respectively.

Table 4.2: Channel assignments using channels 1, 6, and 11 only.

AP	CHANNEL	AP	CHANNEL
1	1	8	1
2	6	9	11
3	11	10	1
4	11	11	6
5	1	12	6
6	6	13	11
7	6	14	1

4.5 Numerical Results

We used LINGO [14] to solve the integer optimization problem. We used the same service area we used in Chapter 3, i.e., a three story building with 14 APs.

First, as is common practice, we assigned channels 1, 6, and 11, which are non-overlapping, to each AP, as given in Table 4.2. The resulting channel assignment map is shown in Fig. 4.2. Calculating the interference, as given in Table 4.3, yielded that AP 7 and AP 8 suffered larger channel interference than other APs because they are located on the second floor. Therefore, channels should be carefully assigned to these APs to reduce interference.

We generated an optimal channel assignment, as given in Table 4.4, and created the optimal channel assignment map, as shown in Fig. 4.3. The algorithm yielded that AP 7 and AP 8 are assigned to channels 10 and 5, respectively. Interference is reduced compared to the previous assignment, when we only used channels 1, 6, and 11, as given in Table 4.5. The interferences at each AP when using only channels 1, 6, and 11, and when using the optimal channel assignments are shown in Fig. 4.4.

In Fig. 4.5, we increased the number of APs from 14 to 30 in our three story building, and analyzed the average interference as a result of using different numbers of available channels.

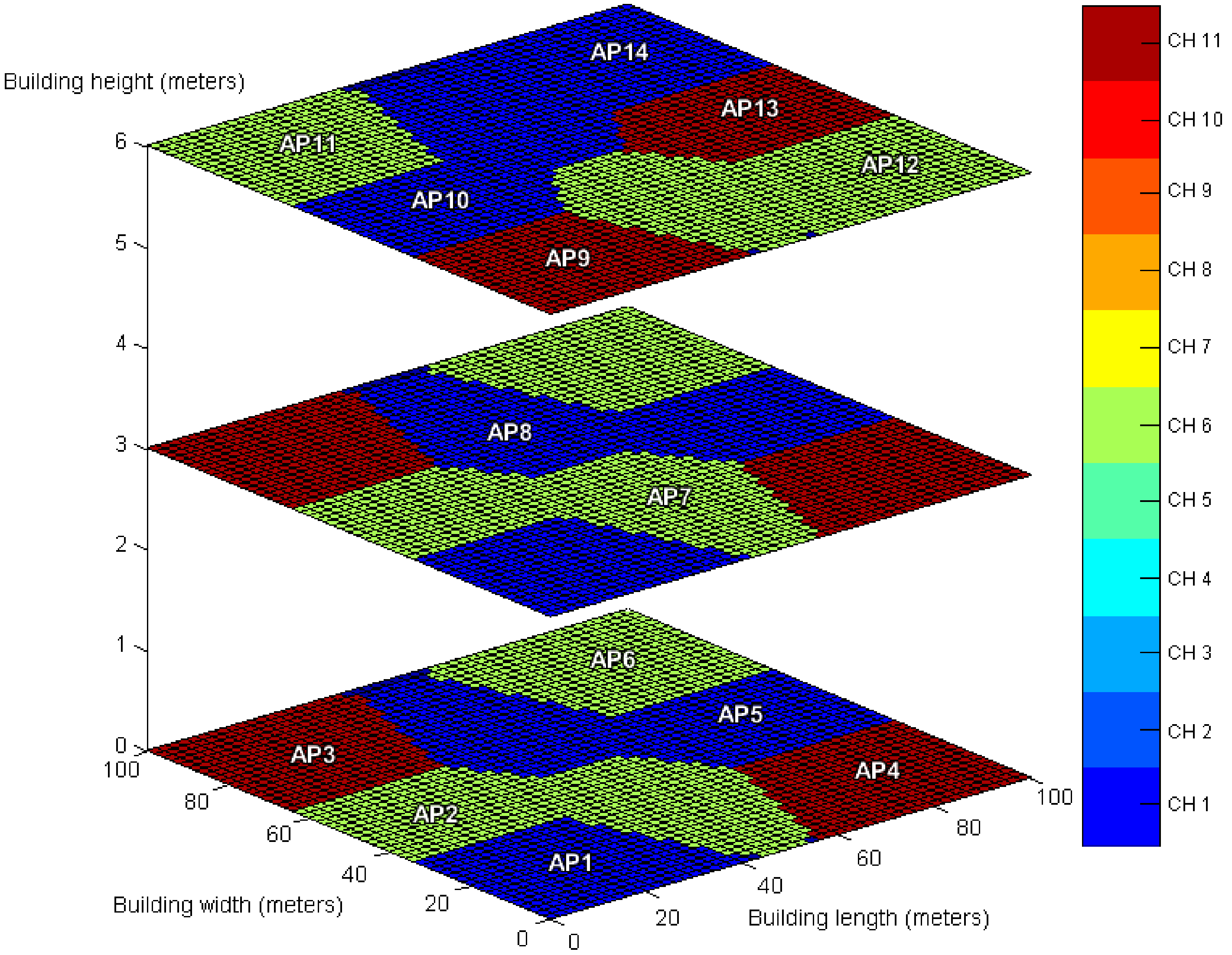

Figure 4.2: Channel assignment map using channels 1, 6, and 11 only.

Table 4.3: Total interference at APs with channels 1, 6, and 11. The average relative interference is 0.00682.

AP	INTERFERENCE	AP	INTERFERENCE
1	0.00643	8	0.01101
2	0.00858	9	0.00303
3	0.00249	10	0.00878
4	0.00546	11	0.00662
5	0.00878	12	0.00635
6	0.00418	13	0.00558
7	0.00918	14	0.00913

Table 4.4: Optimal channel assignment.

AP	CHANNEL	AP	CHANNEL
1	1	8	5
2	11	9	6
3	6	10	1
4	6	11	11
5	1	12	11
6	11	13	6
7	10	14	1

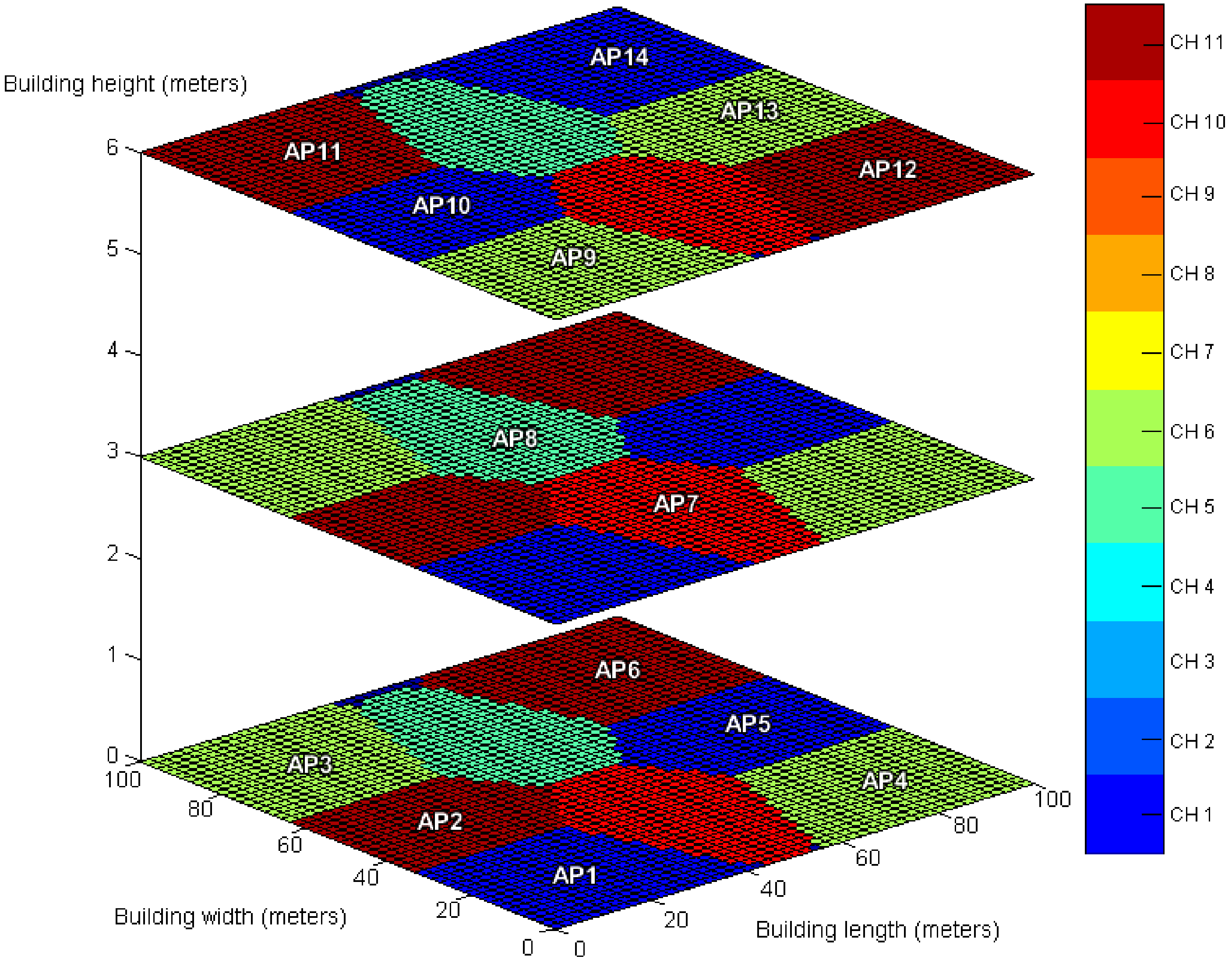

Figure 4.3: Optimal channel assignment map.

Table 4.5: Total interference at APs with optimal channel assignment. The average relative interference is 0.00669.

AP	INTERFERENCE	AP	INTERFERENCE
1	0.00549	8	0.00954
2	0.00797	9	0.00472
3	0.00580	10	0.00638
4	0.00715	11	0.00638
5	0.00638	12	0.00557
6	0.00395	13	0.00857
7	0.00972	14	0.00603

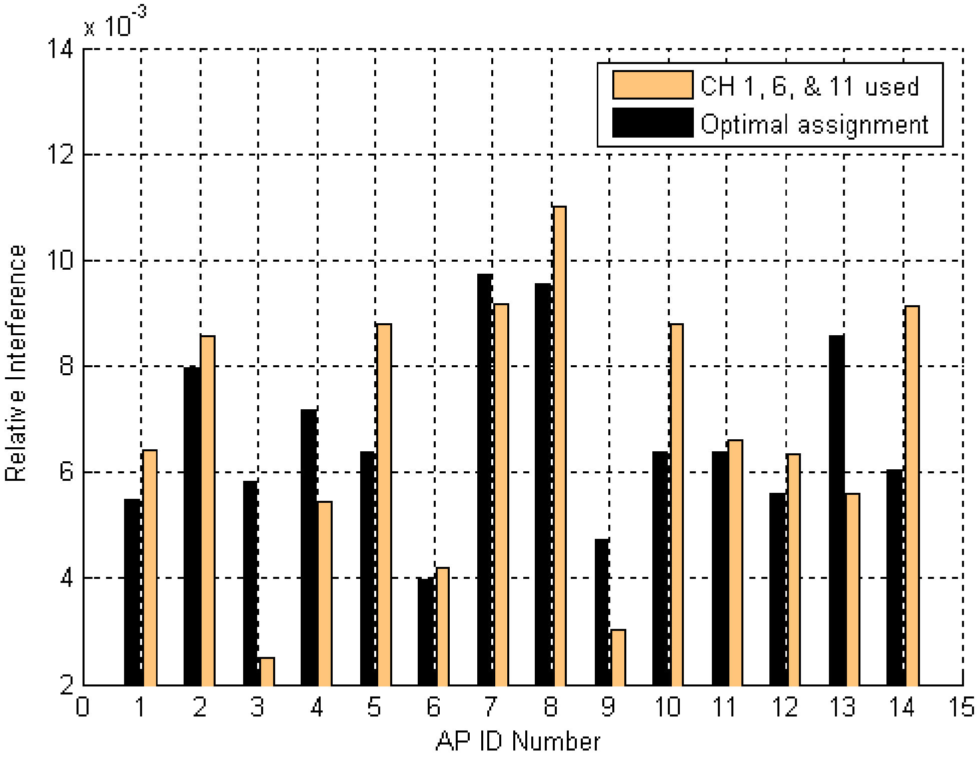

Figure 4.4: The relative interferences of APs when using only channels 1, 6, and 11 and optimal channel assignment.

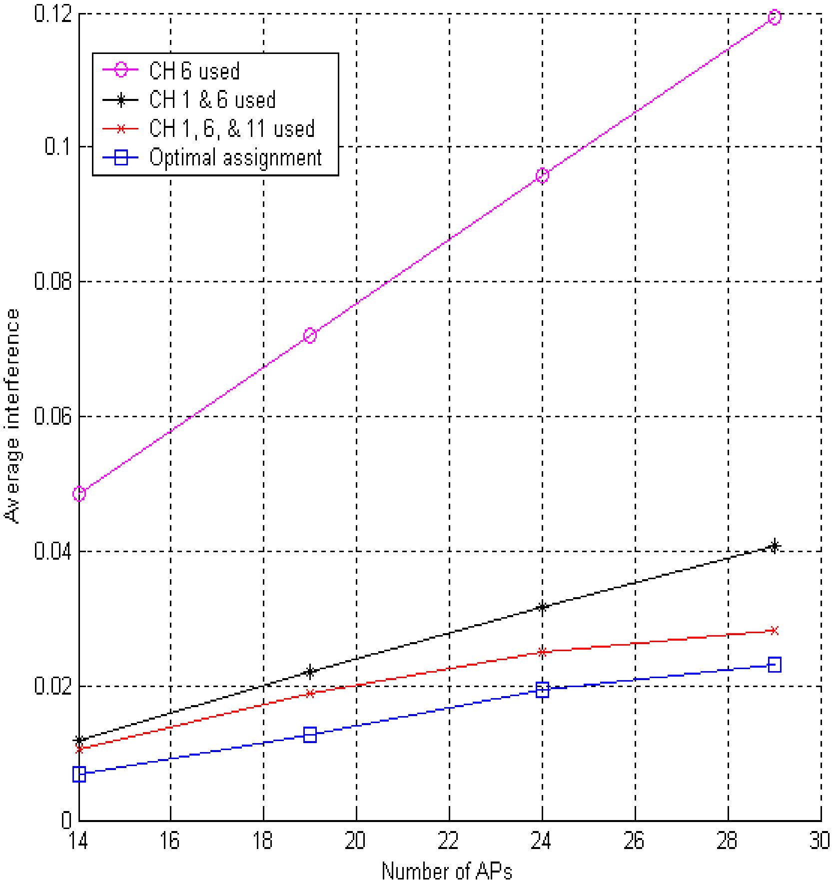

Figure 4.5: Average relative interference across the network as the number of APs is increased.

When we used only channel 6, which is a common factory default channel setting, the average interference increased rapidly when we increased the number of APs. Using channels 1 and 6 reduced the interference greatly. Optimal channel assignment yielded the lowest average interference, and confirmed that using more than the 3 non-overlapping channels, which are channels 1, 6, and 11, helps to minimize the channel interference between APs.

4.6 Summary

We proposed an optimal channel assignment algorithm by formulating an integer optimization problem. By minimizing the interference at each AP, the network will have better throughput. We analyzed a three story building with 14 APs with different channel assignments. Our optimal channel assignment showed that using more than the 3 non-overlapping channels, the average interference across the networks can be reduced. As the number of APs is increased, optimal channel assignment becomes crucial; otherwise interference becomes a limiting factor.

CHAPTER 5

CONCLUSIONS

5.1 Summary

IEEE 802.11 wireless network design includes two major components: placement and selection of APs and assignment of radio frequencies to each AP. APs need to provide certain minimum bandwidth to users located in the coverage area. 802.11 wireless LANs operate in the unlicensed ISM frequency, and all APs share the same frequency. As a result, as 802.11 APs become widely deployed, they start to interfere with each other and degrade network throughput. Therefore, traffic load balancing between APs and optimal channel assignment to APs are crucial tasks when wireless LANs are designed.

In Chapter 2, we investigated the physical layer of the 802.11 standard and explained the details of the MAC sublayer protocol. The 802.11 medium access control (MAC) sublayer protocol provides a contention free and a contention based access control on a variety of physical mediums. It provides an effective and distributed mechanism to coordinate the medium access among APs and stations.

We examined the protocol stack, physical layer, and the MAC sublayer protocol of the 802.11 wireless LANs standards. The transmission medium is shared by all APs and stations. To avoid frame collision, the MAC protocol coordinates access to the medium with CSMA/CA technique along with NAV. Interference and collision degrade network throughput, so intelligent AP selection and optimal channel assignment become paramount procedures when deploying the 802.11 wireless LANs.

In Chapter 3, we formulated the problem of AP selection and traffic allocation by minimizing the congestion of the most heavily loaded APs. By minimizing the bottleneck APs, we can get better bandwidth utilization for the whole network, which will result in higher throughput.

We analyzed a three story building with 14 APs with 20 demand clusters. A demand cluster will not necessarily select the closest AP that has the largest signal level. Our optimization balances the load on the entire network such that demand clusters might select APs that have slightly lower signal levels but still can service the demand clusters and provide ample bandwidth.

In Chapter 4, we proposed an optimal channel assignment algorithm by formulating an integer optimization problem. By minimizing the interference at each AP, the network will have better throughput. We analyzed a three story building with 14 APs with different channel assignments. Our optimal channel assignment showed that using more than the 3 non-overlapping channels, the average interference across the networks can be reduced. As the number of APs is increased, optimal channel assignment becomes crucial; otherwise interference becomes a limiting factor.

5.2 Future Research

We conclude by outlining possible directions for future research:

- Our selection algorithm can be extended to optimize locations of APs. A user can specify the maximum number of APs, and the algorithm would find the optimal placement of APs in a given service area.

- IEEE 802.11b and 802.11g use the unlicensed ISM frequency. Many electric appliances such as microwave ovens, cordless phones, and Bluetooth devices use the same frequency band. Our channel assignment algorithm can be further extended to consider interferences between these electric devices and wireless LANs.

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