PLACEMENT OF ACCESS POINTS IN WIRELESS LOCAL AREA NETWORKS

BY

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This thesis, written by **FAISAL AHMED AL-NASSER** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN SYSTEMS ENGINEERING.**

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Dedicated to

My Lovely Family

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All praise is for ALLAH (SWT), the most compassionate, the most merciful. May peace and blessings be upon prophet Mohammed (PBUH), his family and companions. I thank almighty ALLAH (SWT) for giving me the knowledge and patience to complete this work.

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THESIS ABSTRACT

Name: Faisal Ahmed Al-Nasser
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The use of Wireless Local Area Network (WLAN) in telecommunications can be found in offices, homes, factories, mobile robots and/or environments where physical wiring may be problematic. As the cost of advanced technology continues to drop and various standards have been established, the future trend of wireless communications appears to be very promising. There are basic design elements in WLAN architecture to provide good service for the users like locations, number and transmission power of the Access Point (AP), also known as Base Stations (BSs). The number of deployed stations has a direct impact on the cost of the WLAN. Moreover, the intercell interference is affected by the number of APs and their locations. It is, therefore, always desirable to minimize the number of stations needed to achieve the required Quality of Service (QoS).

Conventionally, it is the network planner's task to manually choose locations and parameters of APs based on prior experience. This manual approach is highly inefficient and time consuming. For this purpose, automatic network planning can substantially reduce the overhead cost of the network, minimize the intercell interference and maximize the QoS. In this work we propose a new placement technique for WLAN APs based on well-known 2-D convolution. The objective of the placement problem is to cover the whole area with minimum number of base stations.

In this thesis, the placement problem is formulated. The proposed solution is then described in details. Simulation results of the proposed solution show its efficiency in handling the placement process. The convolution substantially reduced the complexity of the problem making it feasible to solve. Furthermore, the developed algorithm can deal with arbitrary propagation and demand patterns, using simple graphical interface.

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خلاصة الرسالة

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تاريخ الشهادة: أبريل 2007 م

يعت استخدام الشبكات اللاسلكية ا لية ال الاتصالات هذه الأيام من الأمور الأساسية ال كن أن دها ا كاتب، ا صانع، ا نازل والأماكن ال يصعب توصيل أسلاك الشبكات التقليدية إليها. أضف إ ذلك أن الا فاض ا لحوظ تكلفة التصنيع ا تعلقة بإنتاج التقنيات اللاسلكية ا ديثة و مقدار التطور الكب أنواع التقنيات ا ديثة ا اصة بالشبكات اللاسلكية من ناحية الكم و الكيف ، يبشر ستقبل واعد ذا ا ال. من أجل قيق ا دمة الأفضل ستخدمي هذه الشبكات هنالك عناصر أساسية لابد من توافرها لتقد خدمة جيدة للمستخدم وهذه العناصر تتمثل مواقع ا رسلات اللاسلكية ، عددها وقوة الإرسال ا اصة بكل منها. لذلك فإنه من ا هم الأخذ بع الاعتبار عند تصميم مثل هذا النوع من الشبكات تقليل عدد ا رسلات اللاسلكية لأن ا تأث ا مباشرا على التشويش ماب ا رسلات اللاسلكية إذا كثر عددها مكان مع وبالتا سوف يقلل من جودة ا دمة لتلك الشبكة. أضف إ ذلك أن مواقع و عدد هذه ا رسلات من العناصر ا امة عملية التخطيط لبناء الشبكات اللاسلكية. لذلك ولغ ه من الأسباب فإن عملية إ اد ا وقع الأمثل للمرسلات اللاسلكية هي من أصعب ا راحل ال تاج إ حل جيد و دقيق. لذلك فإن ا صمم ا ب يستطيع أن يقوم ذا العمل من خلال خ ته ويقوم بتعي ا واقع ا ناسبة وكذلك بقية ا دخلات. لكن يبقى هذا النوع من ا لول ليس ديا دائما خاصة حال أصبح البناء أكثر تعقيدا و أك مساحة. لذلك ولغ ه من الأسباب يقوم هذا العمل باستحداث طريقة جديدة وسريعة ل مشكلة إ اد ا وقع والعدد الأمثل للمرسلات اللاسلكية لتقد التغطية ا طلوبة. تعتمد هذه الطريقة على الالتفاف الثنائي الأبعاد و تتمحور فكرة العمل على توف أك تغطية لاسلكية كنة بأقل عدد كن من ا رسلات اللاسلكية و سوف تستعرض رسالة ا اجست هذه تفاصيل هذه الطريقة ا ديدة. هذه الرسالة صياغة هذه ا شكلة رياضيا ويلي ذلك تفصيل كيفية الوصول إ النتائج. ولقد أثبتت نتائج ا اكاة ذا العمل قدرته وفعاليته معا ة هذا النوع من ا سائل. أضف إ ذلك أن ا وارزمية ا طورة ال استخدمت هذا العمل تستطيع التعامل مع أنواع متعددة و تلفة من ا عطيات باستخدام واجهة رسومية بسيطة.

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أبريل – 2007

NOMENCLATURE

In the following, the variables used in the thesis are listed.

$\boldsymbol{N}$	=	Total number of Access Points.
$\boldsymbol{F}$	=	Fixed demand pattern matrix of size $(I \times J)$.
$\boldsymbol{A}$	=	$(I_A \times J_A)$ fixed propagation pattern matrix which represent propagation model for the radio antenna.
$\boldsymbol{p(x,y)}$	=	Effective signal power at location (x,y).
$\boldsymbol{a}$	=	Desired Power Threshold.
$\boldsymbol{P}$	=	Power pattern matrix of size $(I \times J)$.
$\boldsymbol{P_n}$	=	Power Pattern Matrix after assigning base station n.
$\boldsymbol{p_{min}(n)}$	=	Minimum Value of the matrix P_n.
$\boldsymbol{X_n}$	=	Location Matrix indicating the location of the n^{th} AP.
$\boldsymbol{c_n(x,y)}$	=	Power Contribution of the n^{th} Access Point to location (x,y).
$\boldsymbol{C_n}$	=	Contribution matrix of size $(I \times J)$ that contains discretized values of $\boldsymbol{c_n(x,y)}$.
$\boldsymbol{f(x,y)}$	=	Signal Attenuation and priority levels at location (x,y).
$\boldsymbol{(u_n , v_n)}$	=	Coordinates of the n^{th} Access Point.
$\boldsymbol{Y_n}$	=	Contribution matrix of size $(I \times J)$ that shows the contribution of each grid point to the power distribution within the grid in case

it is chosen as base station location.

G_n	=	Accumulated power distribution due to antenna *1,2 ,……..n* .
n	=	It is defined as the Access Point number, $n = [\, l , N \,]$.
p_n	=	Transmitter power.
G_t	=	Transmitter gain.
G_r	=	Receiver gain.
λ	=	Wave length.
d_n	=	Distance between point (x,y).
Γ	=	2-d Euclidean space .

CHAPTER 1

INTRODUCTION

1.1 Wireless Networks Background

1.1.1 Evolution of Wireless Networks

Figure 1.1 shows a general view of the evolution of wireless networks. It is well known that the first successful trial to transmit information through the air was done in 1895 by Marconi for a distance of 18 miles [40]. In 1902, he could do the first bidirectional communication across the Atlantic Ocean successfully. The origins of radio based telephony date back to 1915 when the first conversation was established between ships.

In this section we describe some of the key milestone in voice and data wireless technology.

1.1.2 Early Mobile Technology

In 1946, the first public mobile telephone system, known as Mobile Telephone System (MTS), was introduced in 25 cities in the United States [40]. It was very big so it needed to be carried by vehicles. It used analog signaling with half duplex technology. Moreover, it used manual switching with only three channels available. In 1960, Improved Mobile Telephone System (IMTS) was introduced with full duplex, where automatic switching and 23 channels are used.

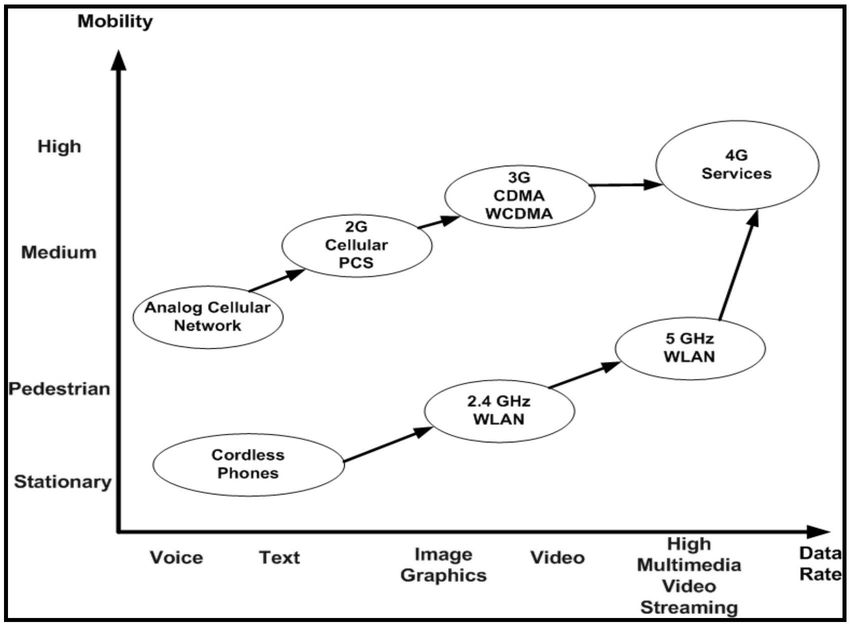


Figure 1.1 : Trend of Wireless Technologies

1.1.3 Analogy Cellular Telephony

Due to the limitations of IMTS, a new concept, which is the cellular concept, was proposed in 1947 but not applied until the 1960s [40]. In this concept, the area of coverage of each AP is called a '*cell*'. Thus, the operating area is divided into a set of adjacent, non-overlapping cells and each cell uses a different frequency to avoid interference (Frequency Reuse). The first generation of cellular systems (1G) was designed in the late 1960s but not deployed until the early 1980s due to some regularity delays. In 1982, the Advanced Mobile Phone System was commercially started in Chicago and it provided only voice transmission. It used the Frequency Modulation (FM) for speech and performed handover decisions for mobiles between cells.

1.1.4 Digital Cellular Telephony

Analog systems had a number of disadvantages and performance limitations which led to the invention of second generation of cellular systems (2G) [40]. The 2G systems represent data digitally. Its devices pass the analog voice into Analog to Digital Converter (A/D). Then, it uses the bitstream to modulate the RF carrier. At the receiver, the reversed operation is performed.

A number of 2G systems have been deployed in various parts of the world. Most of them can support *Short Message Service* (SMS), data transfer (low speeds of 10 Kbps). However, recently, an upgrade was made to these systems, known as 2.5G, which supports more features and higher data speeds.

GSM is the famous 2G technology with 900 to 1800 MHz band which started in 1982 in Europe and the first commercial deployment was in 1992. It was named *Group Special Mobile* and later was renamed *Global System for Mobile Communication*. As far as operation is concerned, GSM defined a number of frequency channels, which are organized into frames and are in turn divided into time slots.

Another advantage of GSM is that it can support several extension technologies which achieve higher data rates for data applications. Two such technologies are *High Speed Circuit Switched Data* (HSCSD) and *General Packet*

Radio Service (GPRS). Both of them use allocation of more than one slot within a frame but the GPRS uses the bandwidth on demand which allows more utilization of the system capacity and supports a higher number of users at a time.

1.1.5 Cordless Phones

Cordless phones initially appeared in the 1970s and they were analog systems [40]. Also, it was limited in range inside homes and offices and it couldn't be used further from a field. After that, the first generation of Digital Cordless Phones was deployed but still with limited features and ranges. Later on, the second generation was introduced, known as called telepoint, which allowed the users to use their cordless phones in a wider range.

1.1.6 Wireless Data Systems

The cellular telephony family is oriented towards voice transmission [40]. However, since the wireless data systems are used for transmission of data, they have been digital from the beginning. The first wireless data system was developed in 1971 at the University of Hawaii as a research project called ALOHANET. This technology was limited in features, capabilities and distance.

Wide Area Data Systems were developed to offer low data rates supporting services like messaging, e-mail and paging. The Mobitex, Ardis and *Multi-Cellular Data Network* (MCDN) are examples of these systems.

Wireless Local Area Networks (WLANs) were used to exchange high speed data within a relatively small region such as a small building or campus. WLAN growth was triggered by US *Federal Communications Commission* (FCC) decision in the mid 1980s to authorize license-free use of the *Industrial, Scientific and Medical* (ISM) bands. The first attempt to define a standard was made by IEEE Working Group 802.4, which was responsible for the development of the token passing bus access method. Later on, they made a working group called IEEE 802.11 with 2 Mbps speed based on Spread Spectrum in ISM bands or infrared transmission. In September 1999, the IEEE 802.11b was approved with a speed of 11 Mbps by extending the performance of the 2.4 GHz physical layer. Also, the IEEE 802.11a with a speed of 54 Mbps in the 5 GHz ISM band was approved, too. The infrastructure of WLAN makes use of a higher speed wired or wireless backbone. In such topology, mobiles nodes access the wireless channel under coordination of an Access Point (AP) which can also interface the WLAN to a fixed network backbone.

Table 1.1 shows different types of wireless data communications, with each having its advantages and drawbacks [40]. Figure 1.2 shows the Data Rate and Coverage for each type mentioned in Table 1.1.

TABLE 1.1: Wireless Data Communications

Wireless Data Type	Properties
Infrared (Ir)	Very high data rates, lower cost, and very short distance.
Narrowband	Low data rates, medium cost, license required, limited distance.
Spread Spectrum	Limited to campus coverage, medium cost, and high data rates.
Personal Communication Service (PCS)	Low data rates, medium cost, citywide coverage
2.5 GHz service , T-Mobile	Global System for Mobile Communication (GSM), medium cost, and worldwide coverage.
Cellular, Cellular Digital Packet Data (CDPD), Mobitex, DataTac	Low data rates, flat monthly rate, and national coverage

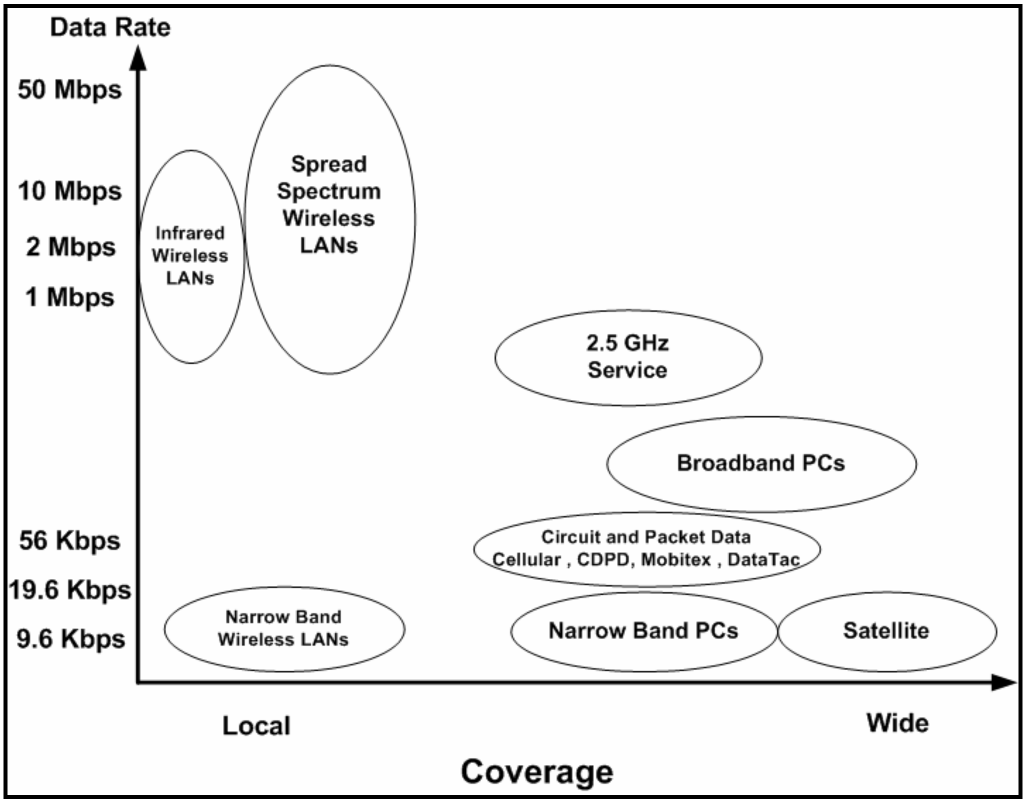


Figure 1.2: Wireless Data Communications

1.1.7 Third Generation Cellular Systems and Beyond

The 2G systems' limitations in maximum data rates, lead to a new generation that was developed to support the new demand of the market. Examples of new demand start from web browsing, reading emails and to more bandwidth-hungry services such as video conferencing and real time applications [40]. In order to support such services the third generation (3G) of cellular systems was initiated by *International Telecommunication Union* (ITU) in 1992. The outcome of the standardization effort called *International Mobile*

Telecommunications 2000 (IMT–2000) comprises different 3G standards. These standards are as follows:

- *Enhanced Data rates for GSM Evolution* (EDGE) or *Enhanced GPRS* (EGPRS) is a digital mobile phone technology that allows for increased data transmission rate and improved data transmission reliability. Also, it is a *Time Division Multiple Access* (TDMA) – based system that evolves from GSM and IS–136, offering data rates up to 473 Kbps. Moreover, it is backwards compatibility with GSM/IS–136.
- cdma2000, a fully backwards compatible descendant of *Interim Standard 95* **(**IS–95) which is known also as cdmaOne that supports data rates up to 2 Mbps.
- *Wideband Code Division Multiple Acces*s (WCDMA) and *Code Division Multiple Access* (CDMA) based system that introduces a new 5 MHz wide channel structure capable of offering speeds up to 2 Mbps.

1.1.8 The Benefits of Wireless Networks

The emergence and continuous growth of wireless networks is being driven by the need to lower the cost associated with network infrastructure and to support mobile networking applications that offer gains in process efficiency, accuracy and lower business costs [39]. The following points summarize in brief the main benefits:

- *Mobility*: it enables the users to physically move while using an appliance, such as a handheld PC or data collectors. Many jobs require workers to be mobile, such as inventory clerks, healthcare workers, police officers and emergency care specialist.
- *Cost Saving*: Because of the lack of a tether the user's appliance and a server, wireless networks offer benefits that reduce networking costs. A very nice example is the installation in Difficult – to – Wire Areas where a road passes between two buildings which need network connections. So, the best solution is to use the wireless link as shown in Figure 1.3.
- *Increased Reliability:* with wireless networks, less number of cables is required. That will reduce downtime and the costs associated with replacing cables in case of cable fault, connector damage or cable cut.
- *Reduced Installation Time:* The deployment of wireless networks greatly reduces need for cable installation process that requires a lot of time.
- *Long – Term Cost Saving:* The movement of people inside the companies and new floor plans requires recabling. That will add new costs like labor and material costs. With wireless network, only relocating the employee's PC is required.

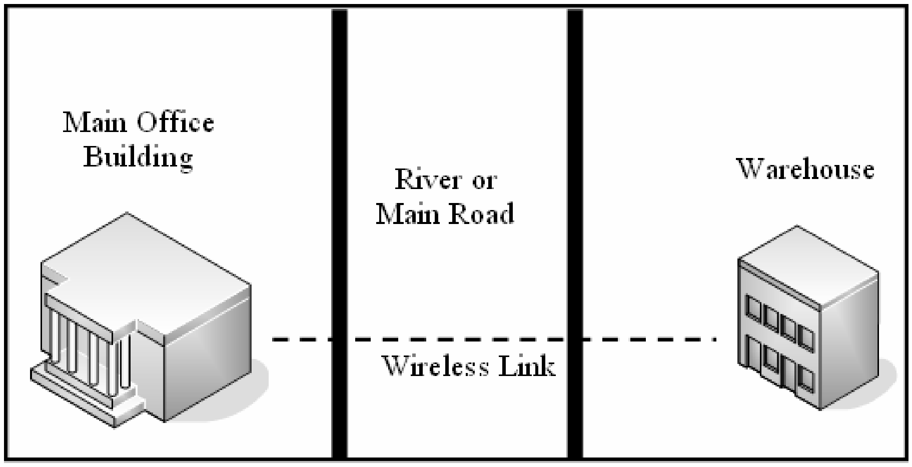


Figure 1.3: Difficult to Wire Example

1.1.9 Wireless Networks; Markets and Applications

Wireless networking is applicable to all industries with a need for mobile computer usage or when the installation of the physical media is not feasible [39]. Such networking is very useful when employees must process information on the spot, directly in front of customers, via electronic based forms and interactive menus. The following are some examples for wireless networks applications:

- *Retail*: the retail organization's need to order, price, sell, keep inventories of merchandise. A wireless network in a retail environment enables clerks and storeroom personnel to perform their functions directly from sales floor.
- *Warehouses*: the staff in warehouses shall manage the receiving, putting away, inventory and shipping of goods. These tasks require the staff to be

mobile and having a handheld computing device with a bar code scanner interfaced via a wireless network to the inventory system.

- *Health Care, Real Estate and Hospitality* are other examples for wireless networks applications.

1.1.10 Wireless Networks Concerns

Network managers and engineers usually have the following concerns that surround the implementations and use of wireless networking. These concerns can be summarized in the following points:

- Radio Signal Interface: it is very important for the planner to put in consideration the behavior of radio signal its properties.
- Power Management: each AP requires a power adjustment according to the required transmission level.
- System Interoperability: all connected devices shall work properly with each other.
- Network Security: the wireless security is very critical especially if the covered area having confidential information such as Banks.
- Connection Problems: to avoid the connectivity problems like connection hand over.
- Installation Issues: like the cost and the future use requirements.

- Health Risks: in some places the wireless signals are prohibited as in the X-Ray rooms in hospitals.

1.1.11 The Future of Wireless Networks

As far as the future of wireless networks is concerned, it is envisioned that evolution will be towards an integrated systems as shown in Figure 1.1 [39, 40]. That will produce a common packet switched (possibly IP–based) platform for wireless systems. This is the aim of the fourth generation (4G) of cellular networks which targets the market of 2010 and beyond. The unified platform envisioned for 4G wireless networks will provide transparent integration with the wired networks and enable users to seamlessly access multimedia contents such as voice, data and video irrespective of the access methods of various wireless networks involved. However, due to the length of time until their deployment, several issues relating to future 4G networks are not so clear and are heavily dependant on the evolution of the telecommunication market and society in general.

1.2 Types of Wireless Area Networks

In today's wireless world, there are many different types of networks offered. All of these different networks are designed to give different coverage areas. The network sizes are shown in Figure 1.4 and 1.5. In the following, we describe these networks in more details [38, 39, 40].

1. *Wireless Personal Area Network (WPAN) – IEEE 802.15:* Typically designed to cover personal workspace. Radios are typically very low powered and do not deliver options in antenna selection thus limiting the size of coverage area (typically less than 20 feet of radius). One such WPAN network is Bluetooth. Applications of this technology include communications between PC and peripheral or between wireless phone and headset. In the WPAN, the customer owns 100% of the network; therefore no airtime charges are incurred.
2. *Wireless Local Area Network (WLAN) – IEEE 802.11:* Designed to be enterprise based wireless networks allowing for complete enterprise applications to be utilized without wires. Typically delivers Ethernet-capable speeds (up to 54 Mbps). In the LAN wireless network, the customer owns 100% of the network; therefore no airtime charges are incurred.
3. *Wireless Metropolitan Area Networks (WMAN) – IEEE 802.16*: Is the official name trademarked by the IEEE 802.16 Working Group on Broadband Wireless Access Standards (commercially known as WiMAX), which defines broadband Internet access from fixed or mobile devices via antennas. Subscriber stations

communicate with access points that are connected to a core network. This is an alternative to fixed line networks that is simple to build and relatively inexpensive. The WMAN networks typically deliver up to broadband speeds (similar to DSL) but are not capable of Ethernet speeds. In the wireless MAN network, the wireless networks can either be a licensed carrier requiring the customer to purchase airtime or may be built out and supported by one entity such as a police department.

4. *Wireless Wide Area Networks (WWAN):* The wireless WAN networks are typically slower in speeds but have more coverage, sometimes covering rural areas. Due to the vast deployment, all WAN wireless networks will require a customer purchase airtime for data transmission.

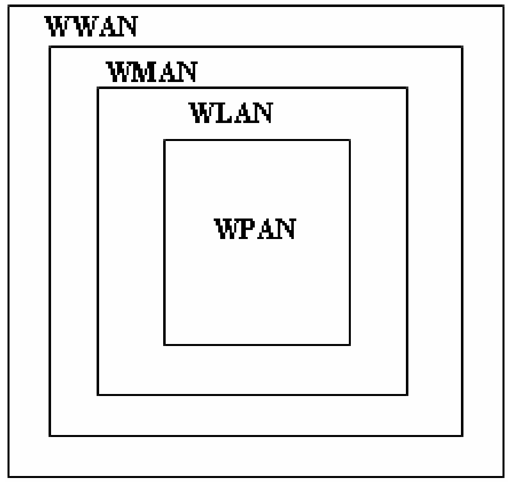


Figure 1.4: Wireless Area Networks Technologies

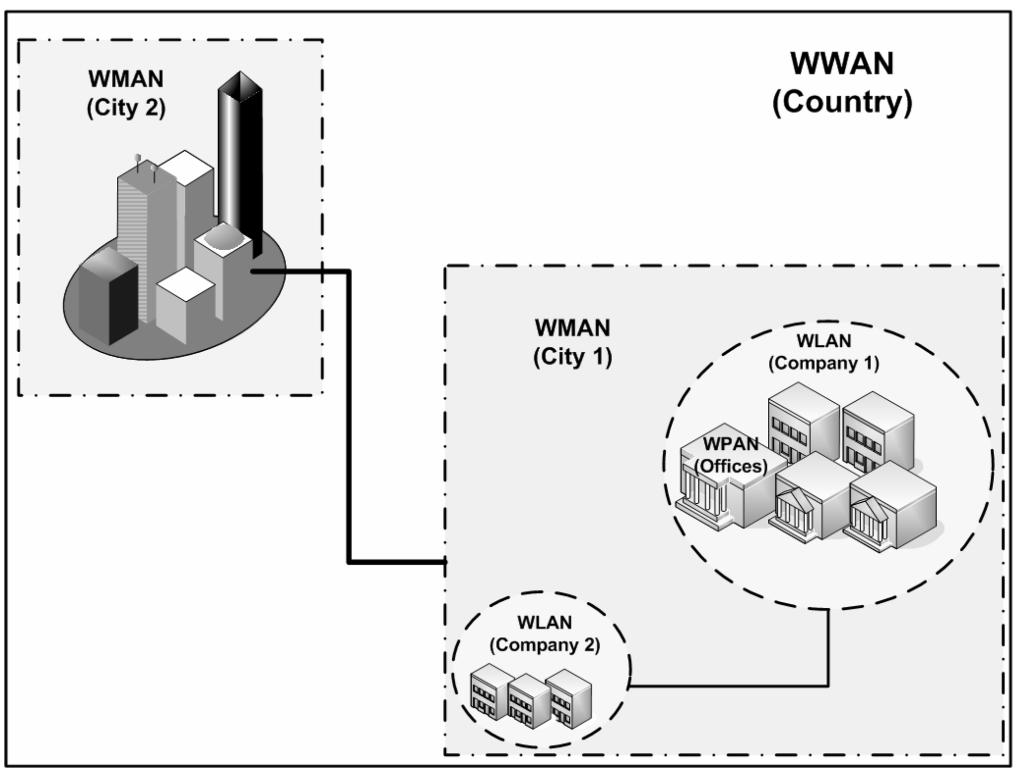


Figure 1.5: Example of Wireless Area Networks Technologies

TABLE 1.2: Wireless Area Networks Technologies (Summary) [39, 40]

	WPAN	WLAN	WMAN	WWAN
Standards	Bluetooth	802.11a , 802.11b , 802.11g	802.11 MMDS , LMDS	GPRS, GSM, CDMA, 2.5G, 3G
Speed	< 2.1 Mbps	2 → 54 Mbps	22+ Mbps	10 → 384 Kbps
Range	Short	Medium	Medium - Long	Long
Applications	Peer to Peer Device to Device	Enterprise Network	Fixed, Last Mile Access	PDAs, Mobiles, Cellular Access

The above Table 1.2 summarizes the main features of the Wireless Area Networks. Moreover, the following will show brief information about WLAN standards as well as in the Table 1.3.

IEEE 802.11b (2.4 GHz)

The 802.11b standard, the most widely deployed wireless standard, operates in the 2.4 GHz unlicensed radio band and delivers a maximum data rate of 11 Mbps [39, 40]. The 802.11b standard has been widely adopted by vendors and customers who find its 11 Mbps data rate more than adequate for their applications. Interoperability between many of the products on the market is ensured through the Wi-Fi™ certification program. Therefore, if your network requirements include supporting a wide variety of devices from different vendors, 802.11b is probably your best choice.

IEEE 802.11a (5 GHz)

The IEEE ratified the 802.11a standard in 1999, but the first 802.11a compliant products did not begin appearing on the market until December 2001 [39, 40].The 802.11a standard delivers a maximum data rate of 54 Mbps and eight non-overlapping frequency channels resulting in increased network capacity, improved scalability, and the ability to create microcellular deployments without interference from adjacent cells. Operating in the unlicensed portion of the 5 GHz radio band, 802.11a is also immune to interference from devices that operate in the 2.4 GHz band, such as microwave ovens, cordless phones, and Bluetooth (a short-range, low speed, point-to-point, personal-area-network wireless standard). The 802.11a standard is not, however, compatible with existing 802.11b compliant wireless devices. Organizations with 802.11b equipment that want the extra channels and network speed offered by 802.11a technology must install an entirely new wireless infrastructure with 802.11a APs and client adapters. It is important to note that 2.4 and 5 GHz equipment can operate in the same physical environment without interference.

IEEE 802.11g (2.4 GHz)

The 802.11g standard has been in draft form since November 2001 and is unlikely to be finalized until 2003 [39, 40]. The 802.11g will deliver the same 54 Mbps maximum data rate as 802.11a, yet it offers an additional and compelling advantage backward compatibility with 802.11b equipment. This means that 802.11b client cards will work with 802.11g APs and vice versa. Because 802.11g and 802.11b operate in the same 2.4 GHz unlicensed band, migrating to 802.11g will be an affordable choice for organizations with existing 802.11b wireless infrastructures. It should be noted that 802.11b products cannot be "software upgraded" to 802.11g because 802.11g radios will use a different chipset than 802.11b in order to deliver the higher data rate. However, much likes Ethernet and Fast Ethernet, 802.11g products can be commingled with 802.11b products in the same network. Because 802.11g operate in the same unlicensed band as 802.11b, it shares the same three channels, which can limit wireless capacity and scalability.

TABLE 1.3: Quick Summary of IEEE 802.11 Standards [30, 38 – 40]

	IEEE 802.11	IEEE 802.11b	IEEE 802.11a	IEEE 802.11g
Max bit rate (Mbps)	2	11	54	54
Fallback rates (Mbps)	1	1, 2 , 5.5	6, 9, 12 , 18 , 24 , 46 , 48	1 , 2 , 5.5 ,6, 9, 12 ,18 ,24 ,46 , 48
Non Overlapping Channels	3	3	8 – 12	3 – 4
Transmit Power [nominal]		40 mW, (16dBm)	100 mW , (20 dBm)	100 mW , (20 dBm)
Band (GHz)	2.4	2.4	5	2.4
Modulation Scheme	FHSS / DSSS	DSSS	OFDM	OFDM
Radius (ft)		100	75	33
Distance Coverage		300 ft (outdoor) 150 ft (indoor)	60 ft	1000 ft. under ideal conditions, 150 ft. indoors, 300 ft. outdoors, under normal conditions
No. of APs		every 200 ft in all directions	every 50 ft	every 50 ft
Devices Using the Standard		Apple, Linksys, Lucent, Cisco	Linksys, Intel, Lucent, Proxim, Cisco; chipsets made by Atheros and Radiata	Apple, Linksys, Lucent, Cisco, Buffalo, Belkin; chipsets made by Broadcom, Atheros, Intersil
Security	WEP & WPA	WEP & WPA	WEP & WPA	WEP & WPA
Reasons for choosing the standard		Widely available, Greater range, lower power needs	Greater bandwidth (54Mb),Less potential interference (5GHz) More non-overlapping channels	Faster than 802.11b (24Mb vs. 11Mb)

There are also other standards which are still under development [40]:

- *Task Group d:* to add the requirements and definitions necessary to allow 802.11 WLAN equipment to operate in markets not served by the current standard.
- *Task Group e:* Addresses the support for the quality of service requirements for all IEEE WLAN radio interfaces.
- *Task Group f:* It is Higher layer protocol and mainly for the communication between APs (Inter Access Point Protocol - IAPP) and to support the roaming between multi-vendor APs.
- *Task Group h:* Defines the spectrum management of the 5 GHz band.
- *Task Group i:* Addresses the current security weaknesses for both authentication and encryption protocols. The standard encompasses 802.1X, TKIP, and AES protocols.

1.3 Cell Planning

1.3.1 Overview

The demand trend of the WLANs is increasing rapidly and most of the existing and new buildings' networks will be served by this technology in the future. In Figure 1.5, a basic structure of the WLAN system is shown. In this structure, the Base Station (BS), also called Access Point (AP), is connected to the wired network from a fixed location using a standard Ethernet cable. AP receives, buffers and transmits data between the elements of the WLAN and the wired network infrastructure. An AP will cover from 25 to 64 computers connected at the same time, within a radio range of 100m to 500m depending on the type of AP [30].

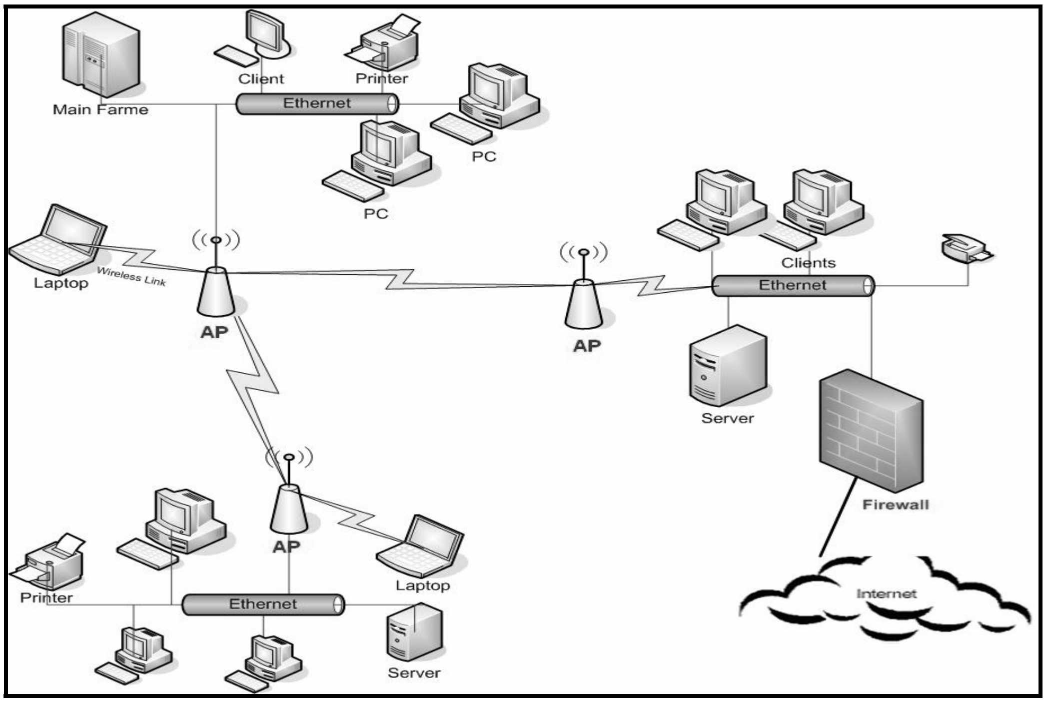


Figure 1.6 : WLAN Basic Structure

The demand for cheaper and better wireless services from the customers is increasing. Also, the move towards smaller cell sizes, that is defined next section, has increased. As a result, it is becoming very important to achieve the optimal design for the cell geometries. Add to that the deployment of the minimum number of APs that will satisfy the Quality of Service (QoS) requirements. One of the main QoS requirements is to achieve the maximum possible coverage. Coverage can be defined as the percentage of area from where it is possible to establish a communication link with at least one of the APs. Capacity is another important parameter in QoS which is defined as the number of users that can be served at a time. Also, the quality of data delivery should be within some acceptable ranges.

1.3.2 Definition of Cell Planning

The presence of physical obstacles and radio interference results in the so called *shadow regions* in wireless networks. When a mobile station roams into a shadow region, its signal strength may drop significantly and calls may even drop completely. To maximize the network coverage in cellular networks, *careful cell planning is required.*

Cell planning can be defined as *a method of how to divide the concerned area into geometrical shapes (cells) that guarantees the delivery of required services for each cell*. Figure 1.7 shows an example of cells where a mobile network is composed of several cells and each cell is covered by antenna that can be omni-directional or uni-directional. Figure 1.8 shows typical free space propagation patterns of omni-directional and uni-directional antennas. In reality, obstacles exist that defuse the signal propagation resulting in non-uniform propagation patterns.

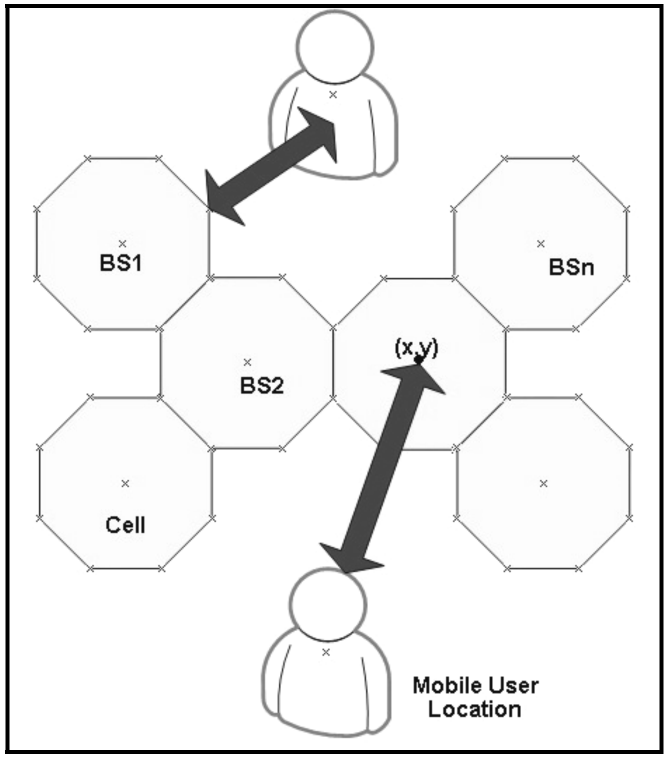


Figure 1.7 : Example of Wireless Network Cells

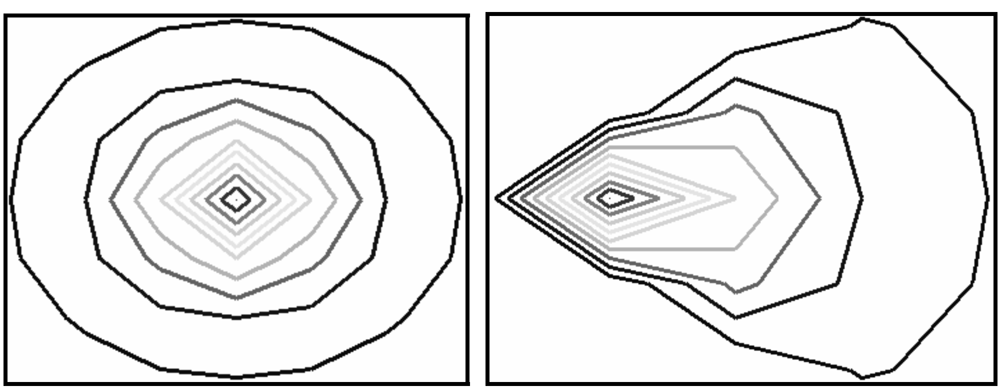


Figure 1.8 : Typical Free Space Propagation Patterns of Wireless Antennas

(a) Omni-Directional (b) Uni-Directional

1.3.3 Placement of WLAN Access Points

The placement of APs is a challenging problem, especially when the number of nodes is large. Network designers need to pay substantial attention in placing the APs so as to achieve the required coverage. The AP placement problem can be defined as *the process of determining the minimum number of APs that satisfy certain coverage requirements*. These requirements vary with the necessity. In some cases, full coverage of the area is required. In other cases, partial coverage with maximum economical return or coverage with guaranteed demand supply is required.

1.3.4 Difficulties in the Placement of WLAN Access Points

In most of the AP allocation studies the highlighted points were under (Minimization) to minimize the Cost, Interference, and Pathloss [2 -30]. To deploy a wireless network, there are main objectives that need to be taken into consideration. These objectives are strongly related to the APs' placement and they are as follows: *Capacity*, *Coverage*, *Quality* and *Costs*.

Moreover, minimizing the required number of APs will minimize the overall cost. In addition, indoor areas have many constraints that need to be taken into consideration when planning and deploying a WLAN, some of which are:

- Walls of different types can attenuate the signal with different attenuation factors.

- Obstacles such as objects, trees and furniture, can affect the signal in various ways, e.g. multipath, shadow fading, etc.
- Density of users in one location could vary suddenly.
- Increasing the number of AP usually increases the inter-cell interference and add extra unnecessary cost.
- The design requirements may vary and therefore the algorithm should satisfy them. (e.g. a design requirement could be the overall percentage coverage).
- Determining the problematic locations which are difficult to deploy the APs.
- Limits on Signal Coverage due to the physical properties of the signals.
- Data Rates are usually limited in the typical scenarios.
- Other possible problems could be: Hidden node, Near-Far Effects, Multi-path fading, Non line-of-sight problem and finally connection handovers from one AP to another, and back, causing breaks in end users access.
- Physical faults of the end-to-end communication connection in the WLAN with redundant APs include:
    - *Node faults:* Node faults are caused by either hardware or software faults in a node. Typical node faults in a AP may be introduced by a strong interference source (e.g., a microwave oven) placed near the AP and result in the incapability of the AP to receive data from other nodes. Node faults in secondary APs in the Forwarding configuration may be the result of power failure due to the APs limited battery life.

- *Link faults:* Link faults are introduced by a mobile terminal entering a shadow area. When this happens, the communication between the mobile node and the AP is lost and the ongoing service is interrupted.

1.4 Thesis Objectives

The main objective of this thesis is to determine the minimum number of APs that guarantee pre-determined power coverage all over a given geographical region. To find the optimal number of APs required, we will introduce a new technique which is based on the two-dimensional convolution. The solution approach can be summarized as follows. The cell planner provides a color coded map. The color codes indicate the demand level in each part of the map. The algorithm then determines the minimum number of APs and their locations that will satisfy the coverage demand.

The thesis has six main objectives. These objectives are listed as follows:

1. A concise model for the WLAN AP location problem will be developed.
2. A solution approach for the model will be developed. The developed approach is simple, intuitive and can be of low complexity.
3. Decrease the complexity of computations of the developed solution approach. This is achieved by some modifications on the algorithm structure to reduce the amount of resources, number of operations (e.g. multiplications) and speed up the processing by optimizing the 2D convolution process.
4. Compare the solution approach used in this work with that of other proven methods like genetic algorithm.

5. Practical means of implementing the proposed approach will be developed. These means will serve as guide-lines for implementing the approach.
6. Developing software with a GUI that makes the implementation of the solution simple and efficient.

1.5 Thesis Organization

The remainder of this work is organized as follows. Previous works related to WLAN APs placement are reviewed and classified in chapter 2. Moreover, the problem and scope under consideration will be defined. Chapter 3 presents the mathematical formulation of the proposed algorithm in this thesis. The next chapter, chapter 4, will present a full description of the proposed placement solution. Then, the numerical results and the code descriptions will be presented in chapter 5. After that, the verification of the solution will be presented in chapter 6 and the solution will be compared with some previous works. Finally, conclusions and future work directions will be presented in chapter 7.

1.6 Terms and Terminology

In the following, we define some terms that are used in the forthcoming chapters of this thesis.

1. **Base Station (BS) or Access Point (AP):** A transceiver or AP as 802.11 calls them (BS) connected to the wired network from a fixed location using a standard Ethernet cable [4].
2. **Coverage:** To obtain the ability of the network to ensure the availability of the service in the entire service area [5, 16].
3. **Capacity:** The number of subscribers (users) served at a time and Bit rate/Bandwidth provided [30].
4. **Quality:** To satisfy the capacity and coverage requirements and still provide the required QoS [30].
5. **Costs:** to enable an economical network implementation when the service is established and a controlled network expansion during the life cycle of the network. Minimizing the number of AP leads to minimizing the overall cost and hence the interference between AP [16].
6. **Data Rate:** The speed with which data can be transmitted from one device to another. Data rates are often measured in *megabits* (million bits) or *megabytes* (million bytes) *per second*. These are usually abbreviated as *Mbps* and *MB/s,* respectively [30].

7. **Throughput:** The amount of data transferred from one place to another or processed in a specified amount of time. Typically, throughputs are measured in kbps, Mbps and Gbps [39, 40].
8. **Bit Error Rate (BER):** The percentage of bits with errors divided by the total number of bits that have been transmitted, received or processed over a given time period [30].
9. **Pathloss:** is a term used in radio communications to denote the radio wave propagation losses taking place on a signal's path from the transmitter to the receiver [18].
10. **Interference:** is the superposition of two or more waves resulting in a new wave pattern. It usually refers to the interference of waves which are correlated or coherent with each other, either because they come from the same source or they have the same or nearly the same frequency [39, 40].
11. **Cell:** A geometrical shape which covered by radio signals [14, 16].
12. **Cell Planning:** Can be defined as a method of how to divide the concerned area into geometrical shapes (cells) which guarantees the delivery of required services for each cell [14, 16].
13. **Antenna:** A device which radiates and/or receives radio signals [40].
14. **Uni-Directional Antenna:** Antenna that beams signals in arc sector shape [40].
15. **Omni-Directional Antenna:** Antenna that beams signals in circular shape [40].
16. **Uniform Coverage:** Each point in the grid has same level of radio signal [5, 16].

17. **Non-Uniform Coverage:** Not all points in the grid have the same level of radio signal coverage [5, 16].

18. **Hidden Node:** occurs when a node is visible from a wireless hub, but not from other nodes communicating with said hub. This leads to difficulties in media access control [27].

19. **Near-Far Effect:** An unbalanced situation where closer end user gets better signal strength than those having longer link connection [27].

20. **Multipath Fading:** In a radio connection the signal is often received from different paths reflected, penetrated, diffracted and scattered. Changes in amplitude, phase and polarization in the received signal distort the original signal [27, 39]. Figure 1.9 shows how signals get reflects from different objects while Figure 1.10 shows how the multiple images of the signal are combinly received.

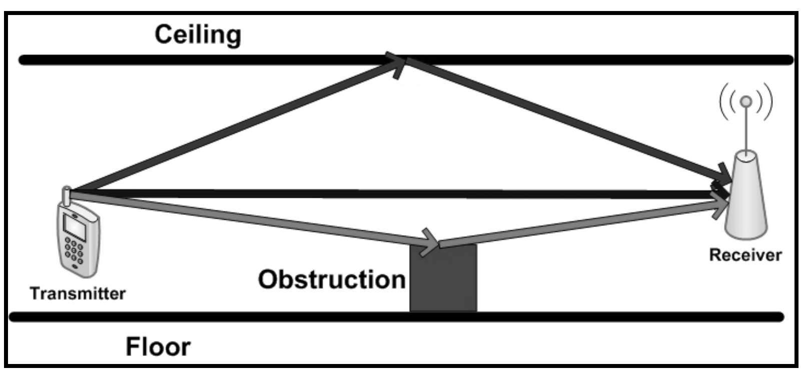


Figure 1.9: Multi-Path Fading

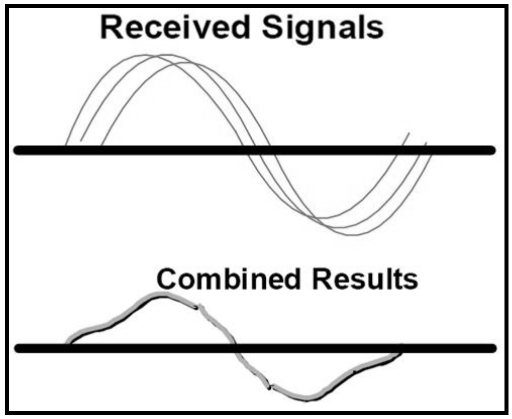


Figure 1.10 : Combined Signal

21. **Non-Line of Sight (NLOS):** It is when the transmitter and receiver have reflectors and/or absorbers between the two antennas [27, 11]. This results in a degradation of the received signal power or "fading".

22. **Connection Handovers:** if you have many APs the user link will switch frequently between available points, sometime with AP A then to B, and back, causing breaks in end users access [27].

23. **Percentage Coverage (*PC*):** is computed as the number of grid points in the coverage area that have power greater than a threshold divided by the total number of grid points in the area**.**

24. **Reflection:** is the change in direction of a wave front at an interface between two dissimilar media so that the wave front returns into the medium from which it originated [9]. As shown in Figure 1.11, when a propagated signal striking a surface, it will either be absorbed, reflected, or be a combination of both and it depends on the physical and signal properties like the surfaces' geometry, texture and material composition.

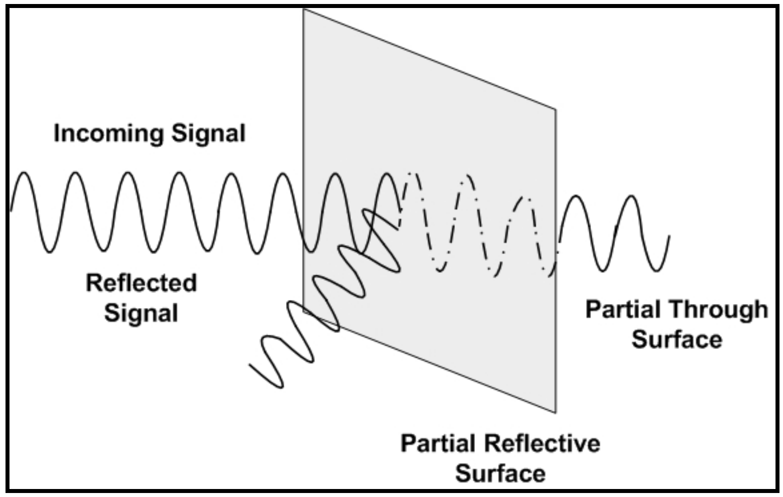


Figure 1.11: Signals Reflection

25. Diffraction: A diffracted signal is formed when the impinging transmitted signal is obstructed by sharp edges within the path [9] as shown in Figure 1.12.

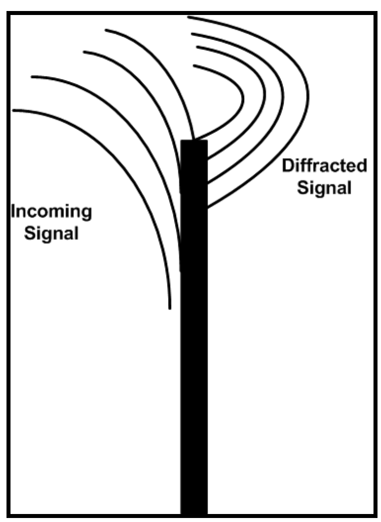


Figure 1.12: Signals Diffraction

26. Scattering: If there are many objects in the signal path, and the objects are small relative to the signal wavelength, then the propagated signals will break apart into many directions. The resultant signal as shown in Figure 1.13 will scatter in all directions adding to the constructive and destructive interference of the signal [9].

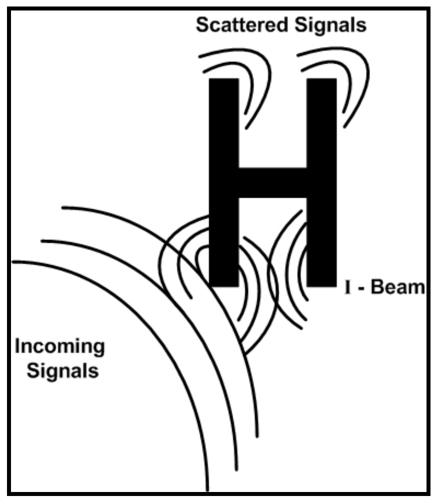


Figure 1.13: Signals Scattering

27. Convolution Theorem: The Convolution theorem states that under suitable conditions the Fourier transform of a convolution is the point-wise product of Fourier transforms [42]. In other words, convolution in time domain equals point-wise multiplication in the frequency domain and vice versa. Let *f* and *g* be two functions with convolution $f \otimes g$; (Note that the $\otimes$ denotes convolution). Let $\mathcal{F}$ denote the Fourier transform operator, so $\mathcal{F}[f]$ and $\mathcal{F}[g]$ are the Fourier transforms of *f* and *g*, respectively. Then

$$\mathcal{F}[f \otimes g] = \sqrt{2\pi}(\mathcal{F}[f]) \cdot (\mathcal{F}[g]) \quad (1.1)$$

where the symbol (·) denotes point-wise multiplication. It also holds the other way round, e.g.,

$$\mathcal{F}[f \cdot g] = \frac{\mathcal{F}[f] \otimes \mathcal{F}[g]}{\sqrt{2\pi}} \quad (1.2)$$

By applying the inverse Fourier transform $\mathcal{F}^{-1}$, we can write:

$$f \otimes g = \sqrt{2\pi}\mathcal{F}^{-1}[\mathcal{F}[f] \cdot \mathcal{F}[g]] \quad (1.3)$$

CHAPTER 2

LITERATURE REVIEW AND PROBLEM DEFINITION

2.1 Background

When Wireless Local Area Networks (WLANs) were first introduced, the focus of the design was to ensure that there was a usable signal in all areas. The cost effective way of providing coverage is to use the minimum number of APs and set them to the maximum transmit power. The standard omni-directional antenna built into the AP produces a circular coverage pattern with a radius of roughly 100m in free space. However, there could be hundreds of users within that area trying for the shared WLAN channel. Further, users located farther from the AP or in areas with poorer reception will transmit at a lower data rate, and that will impact the performance of users with good signal quality (i.e. the lower data rate users take longer to send a message, so other users must wait longer to get access to the channel, in other words, all users will suffer).

Providing access to a service that does not live up to expectations might be as bad as providing no service at all. In planning capacity per user, one must begin with the usable capacity of a WLAN channel and an estimate of how many users will be sharing it. In general, the estimated throughput of a WLAN channel is roughly 50% to 55% of the raw data rate [38, 39]. That estimate assumes all users are in a fairly close proximity to the AP and so are operating at the maximum data rate.

Proper design involves providing signal coverage in all areas, but also ensuring that the network delivers adequate performance for all users in a cell. It should also be noted that wireless LAN design is an ongoing process, so these capacity issues must be revisited as usage grows and more APs/cells are added to the network. Of course, adding more APs also increases the cost of the network.

2.2 Literature Review

This section surveys the works done in the area of WLAN APs optimal placements methods. It covers many techniques which were used to solve this problem. Steepest Descent Method, Simplex Method, Hooke and Jeevs' Method, Genetic Algorithm and Linear Integer Programming Method are examples of these techniques. Each one has its own characteristics. These developments occurred at different times starting from the early 1980's. Moreover, some works where discussing the pathloss modeling and the effect of wall types on the signals. Also, in other works, cell planning was another issue that people tried to optimize.

Saleh and Valenzuela [1] present the results of indoor multipath propagation measurements using 10 ns, 1.5 GHz, similar to radar pulses, are presented for a medium size office building. The observed channel was time varying very slowly, with the delay spread extending over a range up to about 200 ns and rms values up to 50 ns. The attenuation varied over a 60 dB dynamic range. A simple statistical multipath model of the indoor radio channel is also presented, which fits the measurements well, and more importantly, appears to be extendable to other buildings. With this model, the received signal rays arrive in clusters. The rays have independent uniform phases, and independent Rayleigh amplitudes with variances that decay exponentially with cluster and ray delays. The clusters, and the rays within the cluster, form Poisson arrival processes with different, but fixed, rates. The clusters are formed by the building superstructure, while the individual rays are formed by objects in the vicinities of the transmitter and the receiver.

Seidel and Rappaport [2] provided a long study on the path loss model by taking into consideration several types of buildings in terms of materials types, building structures and the use of the building. The main objective was to predict path loss models for 914 MHz inside multi-floors buildings and they have used some system identification techniques to analyze the outputs like linear regression and Minimum Mean Square Error (MMSE). The initial path loss function (*PL*) described as:

$$\overline{PL}(w) \quad \propto \quad \left(\frac{w}{w_0}\right)^t \tag{2.1}$$

Also there is an Absolute Mean Path Loss in Decibels that is defined as path loss from the transmitter to the reference distance w_0 plus the additional path loss described by:

$$\overline{PL}(w)[dB] = \overline{PL}(w)[dB] + 10 \times t \times \log_{10}\left(\frac{w}{w_0}\right) \tag{2.2}$$

This function was reshaped depending in the study case they had. After that, they plot data using AutoCAD into Contours Plots of locations of equal path loss for a given transmitter location. They applied this technique on more than one material type of walls and obstacles in multi-floors buildings.

Holt, Pahlavan and Lee [3] presented a graphical user interface program that uses a *Ray Tracing Algorithm* to predict the radio propagation in the indoor radio channel from the layout of the floor plan. The program allows the user to interactively specify the location of the walls in the floor plan, the type of material in the construction, and the location of the radio transmitter and receiver. The equation used to model the multipath radio channel is a linear filter with an impulse response given by:

$$h(t) = \sum_{h=0}^{n} B_k e^{-j\theta_k} \sigma(t - \tau_k) \qquad (2.3)$$

where β_k's are the real positive gains, the θ_k are the phase shifts and the τ_k's are the propagation delays of all channel paths. The ray tracing algorithm determines the magnitude, phase, time of arrival, and direction of every signal path between the specified radio transmitter and receiver when an RF pulse is transmitted. The accuracy of the model for a shielded cage is examined by comparing the results with those obtained from empirical measurements. Comparisons are also made between the simulation and the results of measurements in a complex laboratory environment at Worcester Polytechnic Institute.

Stamatelos and Ephremides [4] addressed the problem of improving the spectral efficiency of cellular indoor wireless networks by optimizing the location and power of APs. They have used site-specific, indoor wireless channel prediction models and derived the network access criteria for the mobiles on the indoor floor when the APs employ omni-directional antennas and adaptive antenna arrays. Also, they derived the cost function for the solution for the optimized problem and they present near-optimal solutions that can be obtained.

$$F(q_1, o_1, h_1, \ldots, q_T, o_T, h_T) = \alpha U + (1-\alpha) I \qquad (2.4)$$

Where U is the size of the uncovered area, I is the size of interference area, $\alpha \in [0,1]$. After that, they compared the omni-directional and adaptive antenna arrays and they showed the properties of each of them and second type was showing better results. Also, they have done their optimization over Continues and Discrete spaces where steepest-descent method and neural network used respectively. Finally, they have built GUI program for indoor wireless networks design to be helpful tool for such studies.

Tsung and Ephremides [5] considered the problem of selecting both the AP locations and transmission power of cellular communication system based on the information of communication traffic distribution. The main objective is to maximize the minimum throughput among the mobiles. The mobility model for each mobile is assumed to be random walk and independent of other mobiles. The maximum throughput region and the scheduling policy which can have such a throughput region are characterized. Then the optimal locations and powers of APs are solved numerically.

K.C. Li and Wong [6] proposed an optimal placement solution for a AP with picocell power range, operating at 1800MHz, situated on stairs of a multistory office building. Analysis of the measurement results indicates that > 10m difference in coverage range could be achieved from the path loss models of different base placements.

$$PL(z) = S + 10t\log(mz) \qquad (2.5)$$

where *PL* is pathloss in dB, *S* is pathloss at 1 m (dB) , *t* = power law index , *m* = extended pathloss multiplier and *z* = vertical distance between transmitter (TX) and receiver (RX).

Margaret H. Wright [7] presented a direct search method by introducing the *Nelder – Mead "Simplex" Method* to find the optimal number of APs required. She introduced an objective function for the percentage of coverage within which received power reaches or exceed the specified threshold. Each step of Nelder – Mead method was defined in four steps and they are: Order, Reflect, Expand, Contract and Shrink. However, the Nelder – Mead methods has several limitations which were presented in the paper.

Fruhwirth and Brisset [8] modeled the problem based on the power balance of wireless transmission and it combines a distance dependant term with correction factors for extra path loss due to floors and walls of the building in the propagation path. Also they take in consideration the directional effect of the antenna since the antennas do not beam same energy in every direction. For APs placements they used the *Branch – and – Bound* which is implement the CHR (*Constraint Handler Rule*) that write the rules constraints into simpler one until it gets solved.

Stein [9] discussed indoor WLAN DSSS radio range testing relating antenna type, radiated power, and transmitter/receiver separation to the IEEE 802.11

compliance range at the 2.4 GHz ISM band frequencies. Indoor range performance is shown to depend not only on transmit power and transmission rate, but on the product's response to multipath and obstructions in the environment along the radio propagation path. Consequently, a comparison of the effects of propagation with respect to a WLAN printed antenna and a dipole are investigated in the dense office environment. Finally, to understand propagation effects, a basic overview was presented.

Rodriguez, Mateus and Loureiro [10] their work was concerned with optimal AP placement assignment using *Integer Linear Programming* technique. This approach is traditionally used on cellular phone systems. The problem is to determine the best AP placement to meet demand areas and the percentage of the total area covered with minimum number of AP. The solution developed an *Integer Linear Programming* model that, given the number of available AP and the signal level of each candidate AP on each demand point, provides the best station placement and the total area covered. This approach provides more flexibility than the traditional one. Their model formula was:

$$\max \sum_{\substack{i \in M \\ j \in N}} S_{ij} W_i Z_i \, H_{ij} \tag{2.6}$$

Subject to:

$$\sum_{j \in N} H_{ij} \leq 1 \ , \forall \ i \in M \tag{2.7}$$

$$\sum_{j \in N} R_i \leq S \tag{2.8}$$

$$\sum_{i \in N_j} H_{ij} \leq \left| E_j \right| R_j \quad , \forall \quad j \in E \tag{2.9}$$

$$\sum_{i \in A_k} R_i \leq 1 \ , \forall \quad j \in E \tag{2.10}$$

where:

- M be the demand points set
- E the candidate AP set
- S the number of available APs
- B_k the set of mutually exclusive APs. Given two or more mutually exclusive stations, only one can be selected (installed)
- R_j be the station j, a Boolean variable that assumes value 1 if the station j will be selected and 0 otherwise.
- E_j be the set of points attended by station j
- S_{ij} the signal of station j on point i
- W_i the attendance priority of point i
- Z_i the area of point i
- H_{ij} be a decision variable that assumes value 1 when the point i is assigned to station j and 0 otherwise.

Ranjan Bose [11] considered how to optimally determine the locations for the placement of APs for a wireless system in an urban setting, and the computational requirements associated with it. Also, they proposed a scheme to determine the optimal cell geometries and the minimum number of cells required to cover a given area of interest. The optimality of the AP locations is with respect to the total coverage area using minimum number of APs. Coverage is being defined as the percentage of area from where it is possible to establish a communication link with at least one of the APs. The objective is to provide wireless coverage in a certain area using the minimum number of APs. Moreover, the concept of *Dynamic Programming* was used to solve the resource allocation problem.

Agere Systems [12] describes a floor-plan analysis method that may help the user to determine number of APs required to create a wireless coverage area within a specific building or facility and the optimal placement of such APs. The method used provides an easy way to plan a wireless network in case you want to prepare site verification "off – site" or if you are calculating a rough budget to build a wireless network in your building.

Butterworth, Sowerby, and Williamson [13] considered a study of the problem of placing APs to yield high capacity and efficiency in an in-building direct-sequence code-division multiple-access wireless communication system. A key requirement for solving this problem is a reliable but simple model of in-building propagation. A number of propagation models are considered as part of a system performance analysis and are found to produce widely ranging levels of accuracy. Correlated shadowing is identified as being a 'key' in-building propagation characteristic that has the potential to strongly influence system performance. Propagation models that included correlated shadowing are shown to produce the most accurate estimates of outage probability when there are a number of interferers facing a user. AP deployment is shown to be a dominant factor influencing the levels of correlated shadowing, and consequently, AP deployment is shown to have major implications on system performance. The system performance for a variety of AP deployment strategies has been determined. Results indicate that there is a tradeoff between system simplicity and performance.

Fruhwirth; Maximilianr and Brirret [14] introduced a model for picocellular radio signals inside a building and they consider the path loss model as:

$$L_q = L_{1m} + 10t\log_{10} w + \sum_i k_i Q_i + \sum_j q_j W_j \qquad (2.11)$$

Where:

- L_q the total path loss in dB
- $L_{1m}$is the path loss one meter from the AP.
- t is the propagation factor.
- w is the distance between the AP and receiver.
- k_i is the number of floors of kind i in the propagation path.
- Q_i is the attenuation factor of one floor of kind i.
- q_j is the number of walls of kind j in the propagation path.
- W_j is the attenuation factor of one wall of kind j.

Also they used the *Branch – and – Bound* method to optimize the number of APs required to cover the desired area by using CHR (*Constraint Handling Rules*). However, they used the *Constraint Logic Programming Language* (CLP) and the code was about 4000 lines which really very lengthy but they get a reasonable results.

Huang, Behr and Wiesbeck [15] presented an innovative algorithm for automatic AP placement and dimensioning. A highly efficient optimization strategy forms the core of the proposed algorithm that determines the number of APs, their sites, and parameters to achieve a high-quality network that meets the requirements of area coverage, traffic capacity, and interference level, while trying to minimize system costs, including the frequency and financial costs. First, the *Hierarchical Approach* proposed earlier is outlined and it is applied to place APs for a large-scale network design. Besides, a fuzzy expert system is developed to exploit the expert experience to adjust AP parameters, e.g., the transmitted power, to improve the network performance. Simulation results are presented and analyzed.

Ranjan Bose [16] considered how to optimally determine the locations for the placement of APs for a wireless system in an urban setting, given the cell coverage. An algorithm is presented here that determines the optimal locations of APs without performing an exhaustive search. Using this algorithm, a 20–25% decrease in the number of APs required has been observed for simulated environments. The computational complexity of the proposed algorithm is also discussed in this paper.

Tang, Man and Kwong [17] presented in this paper the *Hierarchal Genetic Algorithm* to optimally locate the APs over a specified area. Within the designed area the signal strength is guaranteed to meet the designed specifications. For realistic modeling the chosen path loss model is a specified type and the density of the obstructions was also taken into account. The quality of the network is highly related to the mean path loss function in terms of distance with respect to n^{th} power:

$$S(d) \propto \left(\frac{w}{w_0} \right)^t \tag{2.12}$$

Where

- S is the Mean path loss
- w_0 is the reference distance chosen as 1 m
- w is the distance between the terminal and APs
- t is the mean path loss exponent indicating how rapidly the path loss is being dissipated as the distance increases.

Also they defined the absolute mean path loss g_i for particular terminal i in decibels can be computed as:

$$g_i = S_0 + 10t\log(w) \tag{2.13}$$

Allocation subproblem was addressed for multiple APs problem and they define some constraints and objectives for their path loss function at the terminal i location. Finally, they found that due to Pareto ranking treatment of the objective functions the simulation demands on the min and the max are trade off with the number of APs.

Han, Park, and Kyu [18] showed that the best AP placement using *Genetic Approach*. A new representation describing AP placement with real number is proposed and new genetic operators are introduced for it. This new representation can describe not only the locations of APs but also the number of those. Considering both coverage and economy efficiency, they also suggest a weighted objective function. Their algorithm was applied to an obvious optimization problem and then is verified. Moreover, their approach was tried in inhomogeneous traffic density environment. Simulation result proves that the algorithm enables to find near optimal AP placement and the efficient number of APs.

Wong, Neve and Sowerby [19] introduced a simple but effective AP placement strategy for use in interference limited *Code Division Multiple Access* (CDMA) systems is proposed. Unlike more commonly applied combinatorial optimization techniques, the proposed strategy uses *Linear Programming*. Since the algorithm is deterministic, an optimal solution is guaranteed. It is shown that this strategy could have application in solving 'real world' problems.

Kumar and Hong Li [20] chose a model for the signal propagation based on a mathematical function numerically defining the degree of coverage and a threshold for the path loss is introduced as a measure for the quality of the signal. The following convex function was formed as follows:

$$f = \frac{1}{R}\sum_{i=1}^{R} w_i \min(QL_{ij}) + \alpha f_1 + (1-\alpha) f_2 \qquad (2.14)$$

where

$$f_1 = \left(\frac{1}{R}\right)\sum_{i=1}^{M} w_i q_i D_i \qquad (2.15)$$

$$f_2 = (w_i p_i D_i) , \quad i = 1,....R \qquad (2.16)$$

$$D_i = \max\left[0, \min\left(QL_{ij} - t\right)\right]_{j=1,......,M} \qquad (2.17)$$

The definition of the used variables as follows:

- *R* is the total number of receivers to be located in the designed area.
- *M* is the number of APs
- W_i is the priority weight
- Q_i is the penalty factor

The parameter f_1 will improve the average path loss that doesn't meet the corresponding threshold and f_2 will ensure that even the worst locations will have acceptable level of coverage. Also, they introduce 7 methods and they compare the results of all of them after applying these algorithms on two different examples. After that, they summarize the results of the comparisons and they proved that *Hook and*

Jeevs, *Genetic* and *Simulated Annealing* algorithms are the recommended of the placement problem because they produce the best results in the tested scenarios.

Park, Yook, and Han-Kyu [21] determined the AP placement automatically using *Genetic Approach*, and the transmit power is estimated considering the interference situation in the case of interference-dominant systems. For applying a genetic algorithm to the AP placement problem, the new representation scheme with real number is proposed. And, corresponding operators such as crossover and mutation are introduced. A weighted objective function is designed for performing the cell planning coverage- and cost-effectively. To verify the proposed algorithm, the situation where the optimum positions and number of APs are obvious is considered. The proposed algorithm is applied to an inhomogeneous traffic density environment, where AP's coverage may be limited by offered traffic loads. Simulation result proves that the algorithm enables to find near optimal AP placement and the efficient number of APs.

Maurer and Wiesbeck [22] investigate radio wave propagation in hospitals. In contrast to other buildings, hospitals are partly constructed of walls that contain metallic layers in their structure. The type of wall depends on the functionality of the room. Measurements were performed at eight discrete frequencies in the range from 42.6 MHz up to 5.2 GHz in all relevant types of rooms such as operating rooms, X-ray, MRT (*Magnet Resonance Tomography*) and others. Due to the big frequency range and in order to investigate extensively the wave propagation properties, various antennas and measurement systems were used. The results show a different behavior of the wave propagation in different rooms of the hospital. Furthermore the results reveal that it is important to consider the room as a whole when determining the attenuation between adjacent rooms. For EM-wave propagation in rooms with metallic layers, slots and openings in the walls are crucial. The measurement data is further used to find a suitable modeling of the walls for simulations with ray-optical methods. The walls are homogenously modeled with multiple layers of different material parameters. This makes it possible to model walls in hospitals with embedded metallic shielding. The results of the simulations agree well with the measurements.

Yang, Smulders and Herben [23] described the wideband measurements conducted at the frequencies 58 GHz and 2.25 GHz in an indoor environment. *Normalized Received Power* (NRP) and *Root Mean Squared* (RMS) delay spread are calculated and used to compare the characteristics of radio wave propagation in both line-of-sight and non-line-of-sight areas at the two frequencies. The results show that on top of the difference in free space, the NRP at 58 GHz is several dBs lower than at 2.25 GHz in average. This difference is also reflected in the fitted log-(virtual) distance NRP models. In the deep shadow region, the poor diffraction level at 58 GHz will reduce the power level, but meanwhile the reflected waves from walls have a strong contribution to the received signal. In addition, it is observed that the radio channel at 58 GHz shows much less time dispersion in terms of RMS delays spread. The results can be quite useful for the 60 GHz system design, which might be very different from the design of conventional systems which operate in the lower frequency bands.

Chen and Garg [24] studied the presence of physical obstacles and radio interference which results in the so called “shadow regions” in wireless networks. When a mobile station roams into a shadow region, it loses its network connectivity. In cellular networks, in order to minimize the connection unreliability, careful cell planning is required to prevent the occurrences of the shadow regions in the first place. In 802.11b/g wireless LANs, however, due to the limited frequency spectrum, it is not always possible to prevent a shadow region by adding another cell at a different frequency. The main objective in that paper is to propose the alternate approach of tolerating the existence of “shadow regions” as opposed to prevention in order to enhance the connection dependability. A redundant AP is placed in the shadow region to serve the mobile stations which roam into that region. Since the redundant AP operates on the same frequency as the primary AP, it does not constitute a separate cell. In fact, the primary and the secondary AP communicate to grant medium access to stations within the shadow region. They consider two configurations, which differ in how the two APs communicate with each other. Secondary AP is connected to the same distribution system as the primary AP, or, the secondary AP acts as a wireless forwarding bridge for traffic to/from the mobile stations in the shadow region to the primary AP. The paper outlines the detail of how redundancy may be implemented by making enhancements to the basic 802.11 channel access protocol.

Daniel B. Faria [25] used the Path loss models to approximate signal attenuation as a function of the distance between transmitters and receivers, being an important building block for both research and industry efforts. In this paper they present experimental data that validates the use of the *Log-Distance Model* both inside and outside a standard building. The measurements were performed using off-the-shelf IEEE 802.11b hardware and with distances varying from 1 to 50 meters. The values found for the path loss exponent agree with previously published results ($\alpha = 4.02$; 3.32). Moreover, linear regression produced models with acceptable standard deviations (< 8 dB) and suggests the occurrence of *Log-Normal Shadowing*, as the deviations from the mean (in decibels) closely follow a Gaussian distribution.

Zvanovec, Pechac and Klepal [26] stated that there are two basic ways to deploy WLAN APs in an indoor scenario: *manual deployment using a site survey based on empirical measurements* or *planning using a software tool with built-in signal propagation models*. In this paper advantages and disadvantages of both ways are discussed. The planning based on propagation modeling is recognized as a highly preferable approach for design of large WLANs. Experimental data in this paper were processed in MATLAB.

RadioNet Finland [27] covered typical questions related with the use of 802.11 standard based equipments in outdoor and indoor networks. First part presents overview of the use of WLAN networks in typical indoor environments. Second part continues and presents the common requirements for outdoor environment and large-scale broadband wireless networks. These questions are then summarized in third section where the use of WLAN in outdoor networks is discussed, highlighting the typical problems and solutions. Technical white paper is concluded then with overview of the support mechanisms and features regarding the use of the 802.11-standard based WLAN technology in large-scale installations.

Binghao Li, Dempster, and Barnes [28] showed that there are essentially two categories of signal strength (SS) based techniques for positioning using WLAN: ‘Trilateration’ and ‘Location Fingerprint’. The prerequisite of the Trilateration method is using a signal propagation model to convert SS to a transmitter-receiver (T-R) separated distance measurement. Utilizing the general empirical model can only obtain a very inaccurate distance of T-R, so a more accurate model is required. The RF signal propagation is very complicated, especially in the indoor environment. However, locally, such as within a small room, the propagation model is better behaved. The proposed hybrid method has two stages. In the first stage, it uses the fingerprinting method with a fast training phase to obtain an estimate of the MU (*Mobile User*) position indicate which room the MU is. In the second stage, Trilateration is used to compute the MU location more accurately. The result shows the proposed method is better than the simple Trilateration method based on general propagation mode, but worse than the fingerprinting method with a medium training phase.

2.3 Problem Definition

In this thesis, we consider the problem of finding the minimum number of WLAN APs that will provide the required coverage over a two-dimensional site map. A heuristic solution will be developed that mainly has two advantages over other studies. The first advantage is in the modeling phase while the other one is in the solution phase. More specifically, the developed algorithm can accumulate any demand patterns as well as any antenna propagation model. The algorithm then uses a novel method to find a solution for the placement problem. This method can be implemented very efficiently and solution can be obtained in a relatively short interface. Cell planners can use this method by simply providing color coded maps of the required coverage. In the following chapter, we formulate the problem mathematically.

2.4 Summary

In this chapter, we have looked at available literature related to the WLAN APs placment problem and briefly discussed the contributions of those studies. To make it simple for referencing we have arranged it based on historical developments. Moreover, the problem conisdered in this thesis was defined.

CHAPTER 3

FORMULATION OF THE PLACEMENT PROBLEM

3.1 Overview

In this study, we consider the optimization of the number of WLAN APs and their locations. These two factors are critical for model development because they can directly affect the quality of service. The formulation will start in the continuous domain and then the developed model will be discretized for final implementation.

3.2 Problem Formulations

The objective of the placement problem is to minimize the total number of APs N such that the effective signal power inside a 2-D Euclidian space Γ is at least equal to a power threshold α. In other words,

$$p(x,y) \geq \alpha \qquad \forall x , y \in \Gamma \tag{3.1}$$

where $p(x,y)$ is the effective signal power at the point with coordinates (x,y). This quantity is affected by the maximum power received from any of the serving APs. In other words, the mobile stations at location (x,y) connect to the APs that has the strongest signal at that location. The effective power is also affected by the interference level at location *(x,y)*. Thus, *p(x,y)* can be expressed as:

$$p(x,y) = \max \{c_n(x,y) + f_n(x,y)\} \qquad for\ n=[l,N] \tag{3.2}$$

The quantity $c_n(x,y)$ is defined as the power contribution of the n^{th} AP to the receiver at coordinates *(x,y)*. This quantity is dependent mainly on the radio propagation and path loss model of the transmitter antenna. For example, for omni-directional antenna in free-space, the quantity $c_n(x,y)$ is given by the well-known Friis equation [30] :

$$c_n(x, y) = \bar{p}_n\, G_t G_r \left(\frac{\lambda}{4\pi d_n(x, y)} \right)^2 \tag{3.3}$$

Where p_n is the transmitter power, n is the AP number, G_t is the transmitter gain, G_r is Receiver gain, λ is wave length and d_n is the distance between point *(x,y)*.

The term *f(x,y)* in equation (3.2) can represent:

- Coverage Demand at point *(x,y)* associated with AP *n*.
- Extra signal attenuation due to natural or man-made obstacles at point *(x,y)*.
- Priority of covering the location *(x,y)*.

In this study, we only consider a static coverage demand that is independent of APs location. This excludes, for example, the shadow fading effects that depend on the APs locations. Other factors such as terrain elevations, electrical characteristics of the ground, coverage priority and forbidden regions can still be represented by this model.

Based on this assumption, the net power distribution can be written as

$$p(x,y) = max\{c_n(x,y)\} + f(x,y) \qquad n=[1,N] \tag{3.4}$$

The term $c_n(x,y)$ represents the supply and $f(x,y)$ represents the demand. The objective of the placement problem is to find the minimum number of APs and their locations that will satisfy the power constraint (3.1).

3.3 Discretization of the Model

To solve the placement model we need first to discretize the variables into finite number of uniform grid points of size $(I\times J)$. The variables $p(x,y)$, $c_n(x,y)$ and $f(x,y)$ are discretized in the 2-D Euclidian space to form the matrices P , C_n and F respectively.

The resulting discrete model is given by:

$$min\ N \tag{3.5}$$

$$\text{Subject to} \quad P = max\{C_n\} + F \geq \alpha \qquad , n= 1,2,\ldots\ldots,,N \tag{3.6}$$

Where P is the power pattern matrix of size $(I\times J)$, C_n is the power contribution matrix of the n^{th} AP that also represents the supply, and F is the demand pattern matrix. Notice that this constraint states that all the elements of the matrix P should be greater than the power threshold α. The matrix C_n can be broken down into the convolution of two matrices as follows

$$C_n = A \otimes X_n \tag{3.7}$$

Where the ⊗ indicates the 2-dimensional convolution. The matrix A of size $(I_A \times J_A)$ is a fixed propagation pattern matrix of the transmitter radio antenna. The matrix X_n indicates the location of the AP n. If we denote this location by the coordinates (u_n, v_n) then:

$$X(i,j) = \begin{cases} 1 & at \quad (u_n, v_n) \\ 0 & eleswhere \end{cases} \tag{3.8}$$

The 2-dimensional convolution is defined by:

$$C_n(i,j) = \sum_{m=0}^{I_a - 1} \sum_{n=0}^{J_a - 1} A(m,n).X_n(i-m, j-n) \tag{3.9}$$
$$0 \le i \le I_a + I_b - 1$$
$$0 \le j \le J_a + J_b - 1$$

Where A is of size $(I_a \times J_a)$, X_n is of size $(I_b \times J_b)$. The convolution values outside the range of the grid are simply truncated. Notice that the objective of the convolution here is to surround the unique non-zero element in X_n with the propagation matrix A. Therefore, the convolution operation in this case can be performed very efficiently by simply shifting the elements of the A matrix by (u_n , v_n). Moreover, we need to introduce one more matrix for the power pattern matrix update:

$$P_n = G_n + F \ , \ n = 1, 2, \ldots, N \tag{3.10}$$

G_n is accumulated power distribution due to antenna 1,2 ,…..n . In other words,

$$G_n = max\ \{G_{n-1}, C_n\} = max\ \{G_{n-1}, X_n \otimes A\}\ , \ G_0 = 0 \tag{3.11}$$

The optimization problem can finally be written as:

$$min \quad \left\| \sum_{n=1}^{N} X_n \right\| \tag{3.12}$$

$$P_N = \max_{n=[1,N]} \{X_n \otimes A\} + F \geq \alpha \tag{3.13}$$

3.4 Summary

In this chapter, we have modeled the placement problem mathematically. First, the model was developed in the time domain. After that, the discretization of the model is done. The model development steps are not much which reflects the simplicity of the proposed model. Also, the 2-D convolution makes the model development simple and easy to solve.

CHAPTER 4

SOULTION OF THE PLACEMENT PROBLEM

4.1 Overview

This chapter presents the proposed solution for the WLAN APs placement problem. The proposed solution is based on a simple and heuristic approach. This approach turns out to offer high flexibility in choosing arbitrary service and demand patterns. It also allows a simple human interface modeling of the problem and provides the solution in a relatively short time.

4.2 Solution Approach

The optimization problem mentioned in equations 3.12 and 3.13 can be solved using the following simple approach. The designer first provides fixed propagation patterns matrix A and demand patterns matrix F. Then, the algorithm will compute the power contribution of every point on the grid to its neighboring points in case it is chosen as AP location. This, of course, takes into account the given demand pattern. Then the point that delivers the minimum power contribution is chosen as the new AP location. After placing each AP, the power pattern P is updated and the process is repeated to choose other APs. The algorithm stops when the minimum power inside the whole region is higher than the power threshold α.

A flow chart of the proposed algorithm is shown in Figure 4.1. To determine the contribution , *consumption* , of each point on the grid to the net power distribution within the grid in case it is chosen as AP location, the propagation pattern A is convolved with the existing power pattern P_{n-1} from previously assigned APs, i.e.,

$$Y_n = A \otimes P_{n-1} \quad , \; P_0 = F \tag{4.1}$$

The matrix Y_n is representing the amount of consumption where the higher consumption point need to be served first and it will consume from matrix A more energy. The role of the convolution here is as follows. For each point on the current power pattern P_{n-1}, the matrix A is centered at that point and dot-multiplied with the intersecting sector of P_{n-1}. The multiplication values are then summed up and the answer is stored at the corresponding point in Y_n.

This convolution process is repeated for all other points in P_{n-1}. The coordinates that correspond to the minimum value of the matrix Y_n, which also represent the higher consumption point, are then chosen as the location of the n^{th} AP,

$$(u_n, v_n) = argmin(Y_n) \tag{4.2}$$

This process will guarantee that the new AP will be located furthest away from previously assigned APs. Once a new AP location is chosen, the matrix X_n is constructed from (3.8).

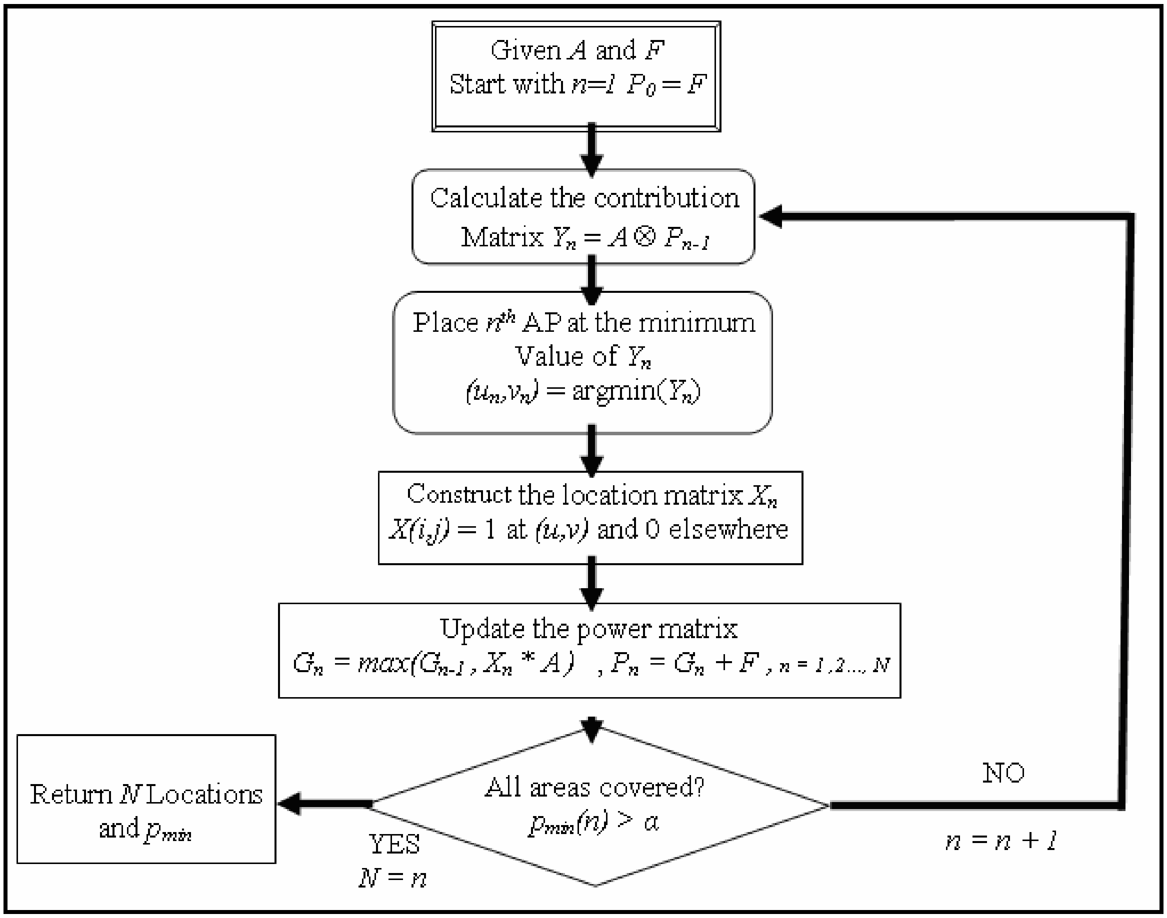


Figure 4.1: Algorithm Flow Chart

The power pattern matrix is then updated as follows:

$$P_n = G_n + F \ , \ \ n = 1 ,2,\ldots\ldots, N \tag{4.3}$$

G_n is the accumulated power distribution due to antennas 1,2 ,…..n . In other words,

$$G_n = max\ \{G_{n-1}\ , C_n\} = max\ \{G_{n-1}\ , X_n \otimes A\ \}\ \ , G_0 = 0 \tag{4.4}$$

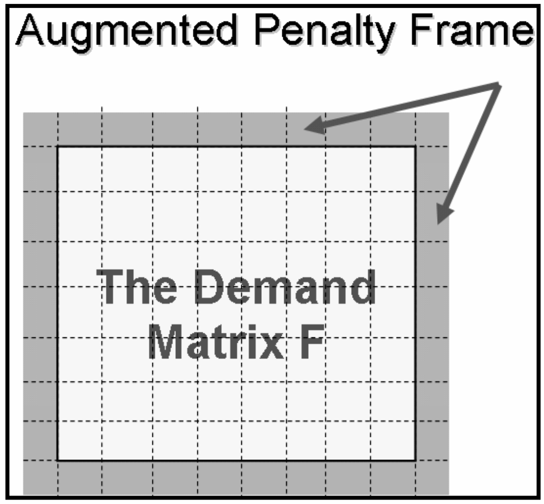
The initial power pattern P_0 is set as the demand matrix F. If the matrix F is all zeros, then the AP will be placed furthest apart, according to the minimum contribution argument discussed above. If F is not empty, the regions where F is negative will produce small convolution values in Y_n and therefore will be chosen first for AP locations. On the other hand, the regions with positive values in F will produce large convolution results and therefore they will be avoided as candidate AP locations. From this discussion, the matrix F works as a weighting matrix that carries the coverage priority for each point on the grid. In summary, given the propagation and demand matrices A and F, the location of the APs is determined by iterating equations (4.1 and 4.3) starting from $P_0 = F$. The algorithm terminates when the constraint (3.13) is satisfied, or equivalently, the minimum power:

$$p_{min} \stackrel{\Delta}{=} min(P_n) \tag{4.5}$$

exceeds the threshold α. The algorithm then returns the total number of APs N, their locations, and the minimum power value p_{min}.

4.3 Penalizing Boundaries of the Demand Grid

Based on the minimum contribution argument described above, the algorithm of Figure 4.1 tends to assign APs at the boundaries so that they will be away from each other as much as possible. This will increase the required number of APs. To solve this problem, one frame is augmented with high positive values f around the demand matrix F as shown in Figure 4.2. The algorithm will then automatically find the optimum frame value that minimizes the total number of APs. The optimal frame value f is usually a positive number that depends on the size of the matrices A and F and their content. In this work, an outer loop is implemented which perform a simple line-search to find the optimum frame value. If two frame values resulted in the same number of APs, the algorithm will take the one that results in the higher minimum power p_{min}. In this way, not only the number of APs will be minimized but also the minimum power will be maximized reflecting improved over-all coverage.



(a)

$$\begin{bmatrix} f & f & f & f & f & f \\ f & -20 & -20 & -10 & -10 & f \\ f & -20 & -20 & -10 & -10 & f \\ f & 0 & 0 & 30 & 30 & f \\ f & 0 & 0 & 30 & 30 & f \\ f & f & f & f & f & f \end{bmatrix}$$

(b)

Figure 4.2: Penalty Frame on the demand matrix F; (a) General Structure (b) Illustrative numerical example.

4.4 Percentage Coverage of the Access Points

The algorithm also computes the percentage coverage for the APs as it assigns them one-by-one. After placing each AP, the accumulative percentage coverage (*APC*) is computed as the number of grid points in P_n that have power greater than the threshold α divided by the total number of grid points in P_n. Based on the value of α , the *APC* value will change and that is clear from the *APC* definition. Figure 4.3 shows an example of *APC* for one experiment.

The percentage coverage (*PC*), as shown in Figure 4.4, is then evaluated by simply computing the difference of the *APC* values. The algorithm returns both *PC* and *APC* with the solution as we shall show in the simulations section. The *PC* is essential information in designing the network. For example, it may allow designers to eliminate those APs with small (or even zero) contribution to the covered area.

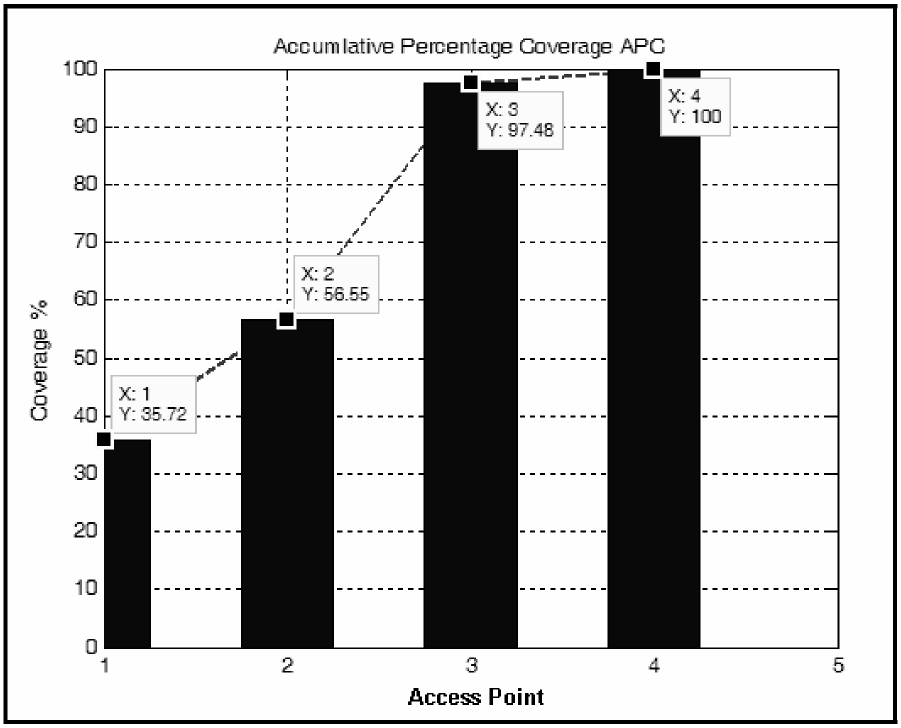


Figure 4.3 : Accumulative Percentage Coverage (APC) for Each AP

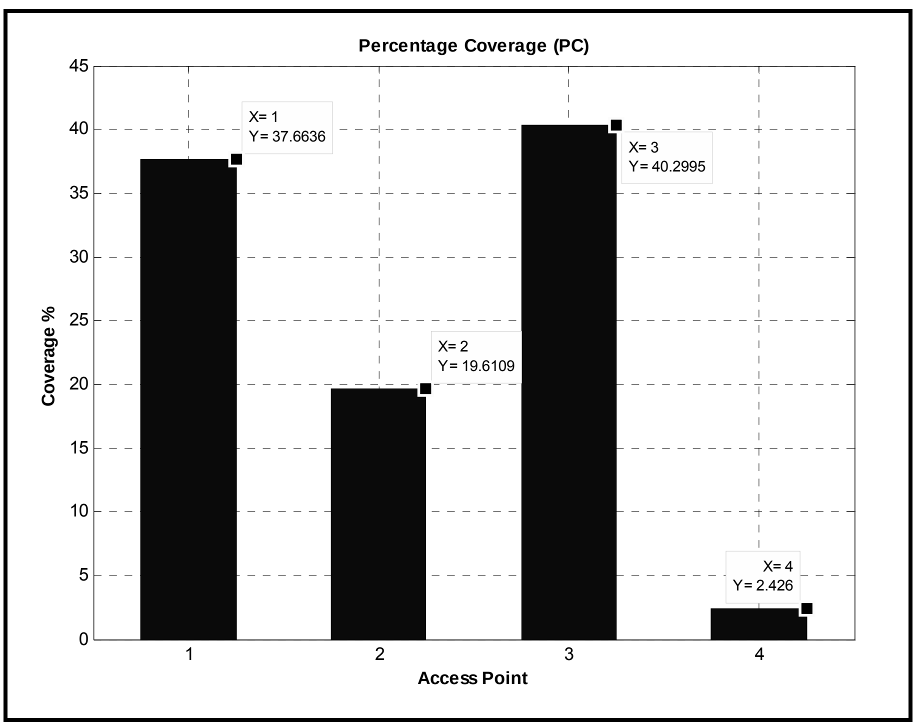


Figure 4.4: Percentage Coverage (PC) for Each AP

4.5 Role of the Propagation Pattern Matrix

The propagation pattern matrix A describes the power propagation and path loss model for the AP antenna. Table 4.1 shows a simple illustration of grid size of 9 × 9 values for matrix *A*. This pattern represents the power propagation of an omni-directional antenna. In this case, the power magnitude starts with 100% at the center of the cell and then decrements inversely proportion to the square of the distance from the AP (according to 3.3). Figure 4.5 shows the contour plot of this matrix where uniform circles of power levels are formed around the AP. The main advantage of the proposed scheme is that it provides major flexibility for network designers to choose arbitrary radio propagation and demand patterns by selecting proper structures of the matrices *A* and *F*. In the following, we describe in more detail the role of these quantities in the network design process. The values in Table 4.1, initially are representing the signal strength in % at a particular point *(x,y)* in the grid. Another example of uni-directional propagation can be represented as shown in Table 4.2. In this case, the values of the matrix *A* are oriented in a certain direction of the 2-dimensional space. The contour plot of this propagation pattern is shown in Figure 4.6.

TABLE 4.1: Omni-directional Antenna and Matrix Representation

3	4	5	6	6	6	5	4	3
4	5	7	9	10	9	7	5	4
5	7	11	17	20	17	11	7	5
6	9	17	33	50	33	17	9	5
6	10	20	50	100	50	20	10	6
6	9	17	33	50	33	17	9	6
5	7	11	17	20	17	11	7	5
4	5	7	9	10	9	7	5	4
3	4	5	6	6	6	5	4	3

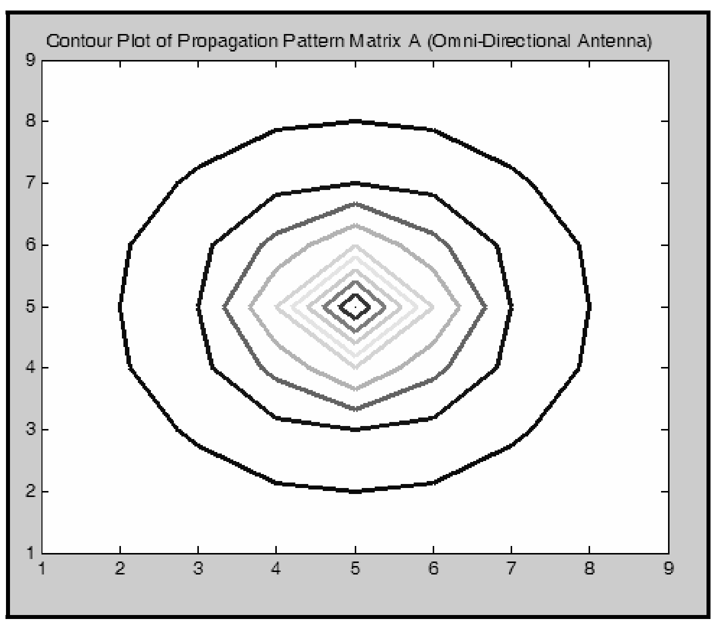


Figure 4.5: Omni-Directional Propagation Pattern

TABLE 4.2: Uni - Directional Antenna and Matrix Representation

0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	5	4
0	0	0	0	0	0	11	7	5
0	0	0	0	0	33	17	9	5
0	0	0	0	100	50	20	10	6
0	0	0	0	0	33	17	9	6
0	0	0	0	0	0	11	7	5
0	0	0	0	0	0	0	5	4
0	0	0	0	0	0	0	0	3

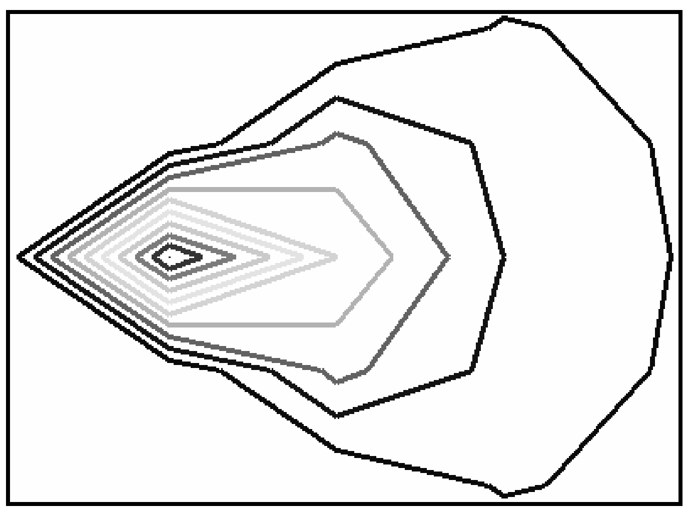


Figure 4.6: Omni-Directional Propagation Pattern

In general terms, the algorithm allows any arbitrary pattern of *A* which makes it suitable for modeling many types of radio antennas.

4.6 Role of the Demand Pattern Matrix

The demand pattern matrix F plays a major role in the design of wireless networks using the proposed algorithm. It gives the designer the flexibility to choose any type of desired demand pattern. For the sake of illustration, Figure 4.7 shows an example of a color-coded map that represents the coverage demand pattern in a given building. Each color represents a level of demand. In this example, the regions with blue color have the highest demand. The green and white colors represent high and normal demand regions respectively. The red color represents no-demand regions where the algorithm should avoid assigning APs at these locations.

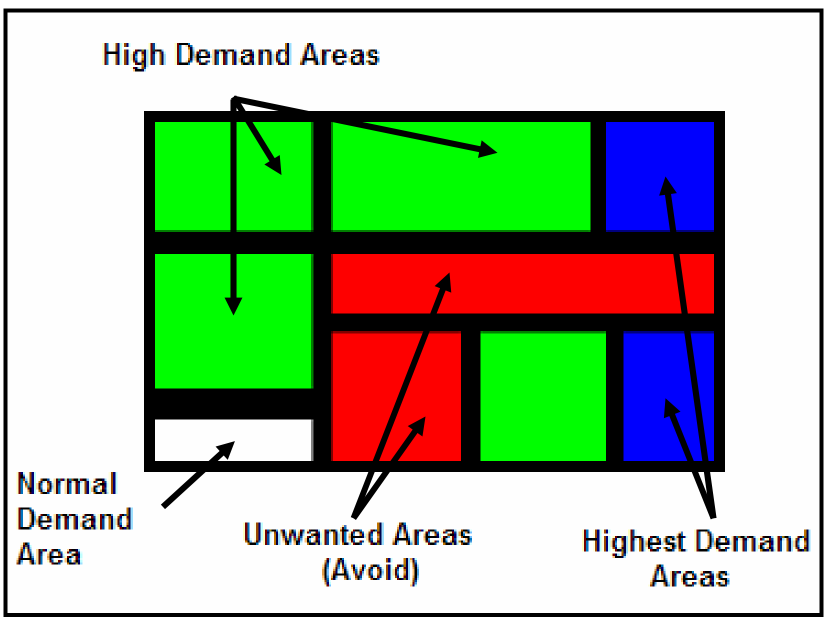


Figure 4.7: Example of building after applying the coloring standards

The algorithm then interprets this color map and builds the demand matrix *F*. The interpretation of the values of *F* is as follows. The high demand regions are reflected in *F* by negative values with magnitude that is proportional to the demand level. The negative values in *F* would result in small contributions in Y_n (see equation (4.1)) and therefore will be chosen first for AP locations. On the other hand, the regions with no-demand are reflected by positive values in *F*. The convolution values in Y_n that correspond to these regions will be large and therefore the algorithm will avoid assigning APs at these regions. Finally, regions with normal coverage priority will be reflected by zero values in the matrix *F*. As a result, the matrix *F* is mostly full of zeros since normal coverage is usually the default case.

Table 4.3 lists the colors values in matrix *F* that will be used by the algorithm. In addition, these values were chosen after many experiments applied on different map sizes, designs, and colors combinations. The values presented in Table 4.3 can be changed based on the customer requirements. Just keep in mind the more negative values shall be used for higher demand areas. Moreover, the bottom part of this table represents the values that can be assigned to walls. The values were given in Table 4.3 for the walls are related to the Attenuation Factor (AF) for each wall type as shown in Table 4.2. As the AF is increases, the values assigned for it will be more positive.

TABLE 4.3: Color Standards

	Color	Demand Scale	Coverage Priority
Demand Coloring			
	White	0	Normal
	Orange (L)	15	↓ Don't Care (DNC)
	Orange (D)	20	
	Purple	30	
	Red	40	
	Brown (L)	50	
	Brown (D)	70	
	Green (L)	-20	↓ Very High
	Green (D)	-30	
	Turquoise	-40	
	Blue (L)	-50	
	Blue (D)	-60	
Walls Coloring			
	Yellow	5	Soft Partions
	Gold	10	
	Gray	80	Very Hard to Pass
	Gray (D)	90	
	Black	100	

TABLE 4.4: Wall Attenuation Factors [9, 32]

No.	Wall Type	AF (dB)
1	Soft Partition	0.8
2	Window Brick Wall	2
3	Brick Wall next to Metal Door	3
4	Plasterboard wall	3
5	Office window	3
6	Cinder Block Wall	4
7	Concrete Wall	5.5
8	Office Wall	6
9	Metal Door in Office Wall	6
10	Metal Frame Glass Wall into Building	6
11	Glass Wall with Metal Frame	6
12	Thick Concrete Wall	9.5
13	Metal Door in Brick Wall	12.4
14	Very Thick Concrete Wall	12.6
15	Floor	30

The design of the matrix *F* helps in substantially reducing the computations in the proposed scheme as will be described in the next section. Using this color-coding technique, a network designer can set any arbitrary relative levels of demand, as shown in Table 4.3. Although the example in Figure 4.7 shows only four color codes, this number of codes can be increased as desired according to the relative demand levels present.

However, as mentioned above, these colors are not fixed to the number provided in Table 4.3. The algorithm can represent as many as required (It is just a matter of definition in the colors table). For example, the Don't Care group can be used for the areas that we don't want the wireless coverage to reach. These scaled values vary from 15 to 70 where for example 70 means that this area should be strongly avoided. The scale 15 is also to be avoided but not as strongly as 70. The group represented by Very High is to be used to color the areas which we want to cover by wireless signals.

The scale ranges from -20 to -60, indicating a higher demand priority as the negative number increases. For example, if the area is covered by light green (-20) this shows a high demand area but it is less priority than dark blue (-60). So, the algorithm will try first to cover areas with the highest priority. In addition, the white color is used for normal demand areas. The attenuation factors in Table 4.4 are useful in calculating the pathloss of the transmitted signals. The algorithm first obtains the AF from the color of the wall. Then, the algorithm uses this factor to update the power matrix after assigning each AP.

4.7 Summary

This chapter described the proposed solution for the AP placement problem and how it works. The regions with positive values in *F* will generate large convolution results and so they will be avoided as AP Locations. In contrast, the regions with negative values will produce small convolution values in Y_n and therefore will be attractive as AP locations. In case *F* has all elements equal to zeros, then the AP will be placed furthest apart. So; *F* is working as a weighing matrix that carries the coverage scaling for each point on the grid. The solution will return the *APC* and *PC* values for each AP.

CHAPTER 5

COMPUTATIONAL EXPERIMENT

5.1 Overview

The developed algorithm in the previous chapter was simulated using a personal computer. A programming code was developed for this purpose. This chapter explains the simulation environment and functionality of the program code. The code primarily contains three main phases: Reading, Analyzing and Writing the final output to the results file and positions in the given map. These phases will be described in detail in the following sections.

5.2 Simulation Environment

In this work, the performance of the proposed placement algorithm will be demonstrated through simple simulation examples. MATLAB 7.0 was used to implement the algorithm on Intel Centrino Duo, 1.83 GHz Laptop computer with 1024 MB of memory. The MATLAB program provides a friendly Graphical User Interface (GUI). It inputs a color-coded map, similar to that of Figure 4.7, in a common image format (BMP) and then generates the corresponding demand pattern matrix F and the propagation pattern matrix A with arbitrary size and values. Also, the program allows the adjustment of several simulation parameters, like demand priority for any color, by manually setting the attributes of the desired color.

The code then computes the optimal number of APs and their locations and then shows them on the provided image. Also, it will show all required charts which represent the coverage in all stages. More specifically, the program will return the following in an output file in a text format:

1- Coordinates of the APs,
2- The final minimum power value, p_{min}
3- The percentage coverage (*PC*) of each assigned AP.
4- The accumulative percentage coverage (*APC*) after assigning each AP.
5- Total processing time.

In our simulations, the size of the matrix F is always scaled down by a factor denoted as the *reduce factor* to control the number of calculations required and hence the processing time while maintaining the details of the image. Also, one can build up a static table for *reduce factors* for previous maps to refer to it in future use. Furthermore, the power threshold is arbitrarily fixed in all simulations to the normalized value $\alpha = 1\%$. This value practically used to ensure that each point in the grid get at least the minimum service required and not less than that and it is depends also on the antenna specifications.

Omni-directional antenna structure similar to that of Figure 4.5 is used for the matrix A. The index at the centers of the APs show the order of assignment of these APs from 1 to n, i.e., the AP that was assigned first has the number 1 in the middle and so on.

5.3 Code Description

The developed program is primarily composed of three main parts: Data Input, Data Processing and Output Results. Each part contains several steps that will be explained in detail in this section.

1- Data Input:

In this part all required information for the algorithm to start will be supplied by the user. Most of this information is taken from the map itself. The following steps will be done for a given building like what is shown in Figure 5.1:

- A detailed map drawing shall be provided as in Figure 5.2. In that figure, we have the 2-D blue print of the building including building dimensions.

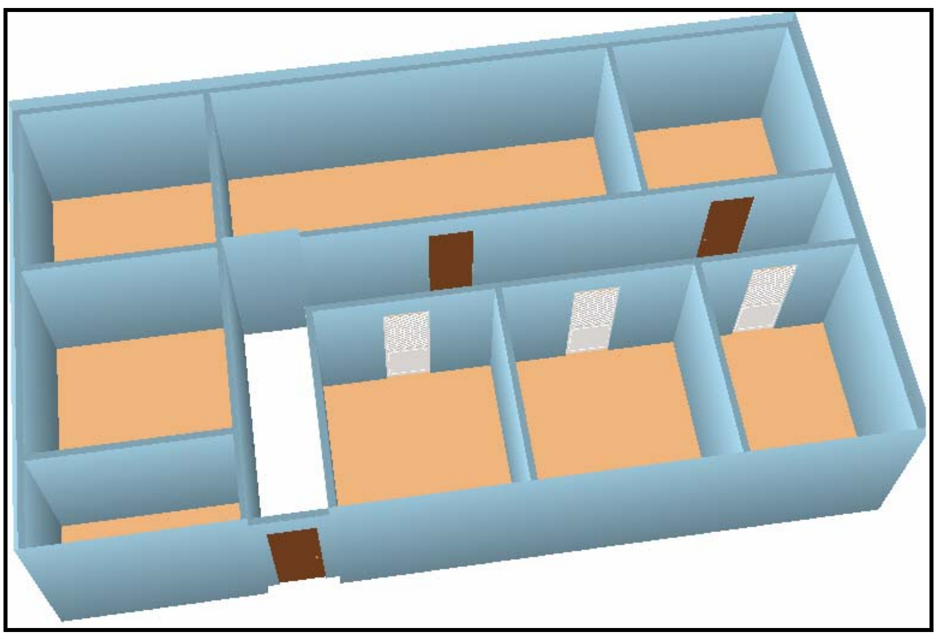


Figure 5.1: Example of Building

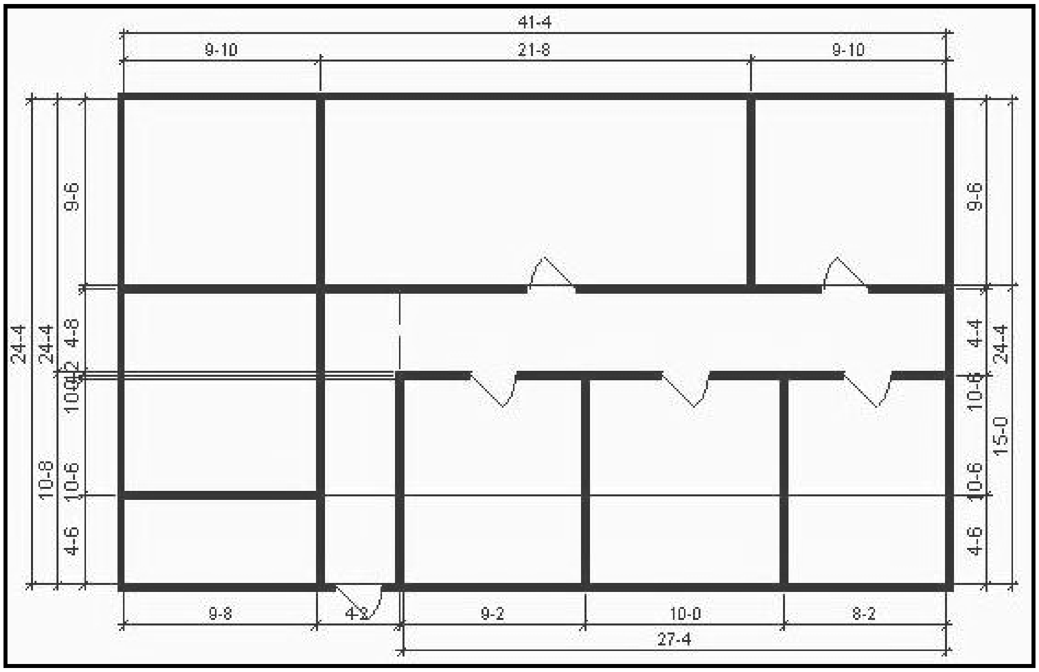


Figure 5.2: 2D Blue Print of the Example Building

- A fixed propagation pattern *A* will also be provided as in Figure 4.6. For antenna propagation, the matrix in Figure 4.5 is an example of Omni – Directional Antenna Propagation Pattern Matrix that will be provided by the designer.
- A fixed demand pattern which is represented by matrix *F* will be generated by coloring the site map according to the demand requirements where each demand level is represented by a certain color. These colors are predefined and described in the Colors Standards in Table 4.3. In Figure 5.3, we view the map after applying the coloring standards.

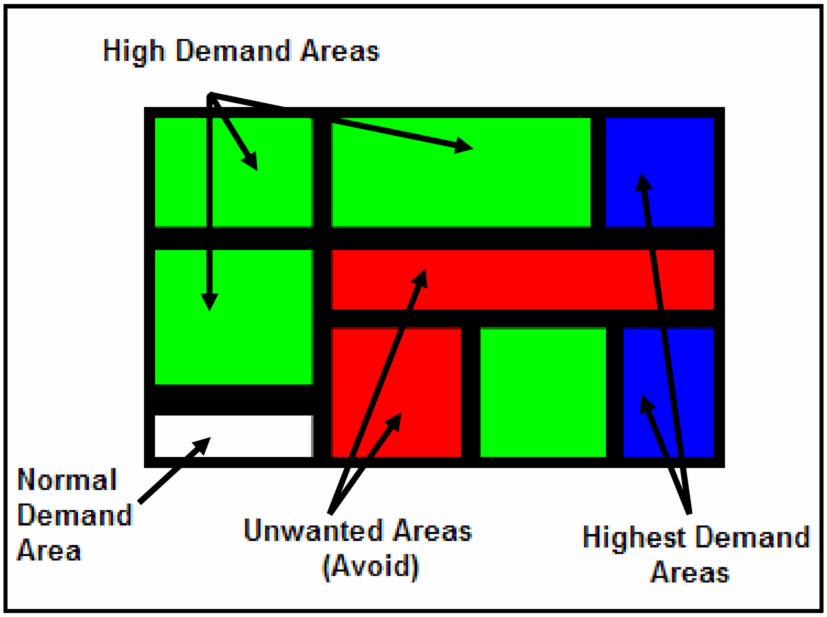


Figure 5.3: Example of building after applying the coloring standards
(Real Example were used in MATLAB)

Graphical User Interface (GUI):

As a part of data input we have developed a Graphical User Interface (GUI) as shown in Figure 5.4 and Figure 5.5 where the user can select the map from a list of files. After that, he can adjust the color values which represent the demand levels as we have explained earlier. In this particular code, the available colors in the GUI are around 16 colors and this number can be increased as required. In addition, there are some parameters like the threshold α which can be adjusted also from the GUI. Also, there is a help document which can be viewed to guide the user how to operate the program. Finally, the final results can be viewed directly by pressing the Result button and Figure 5.6 shows a snapshot of one simulation results.

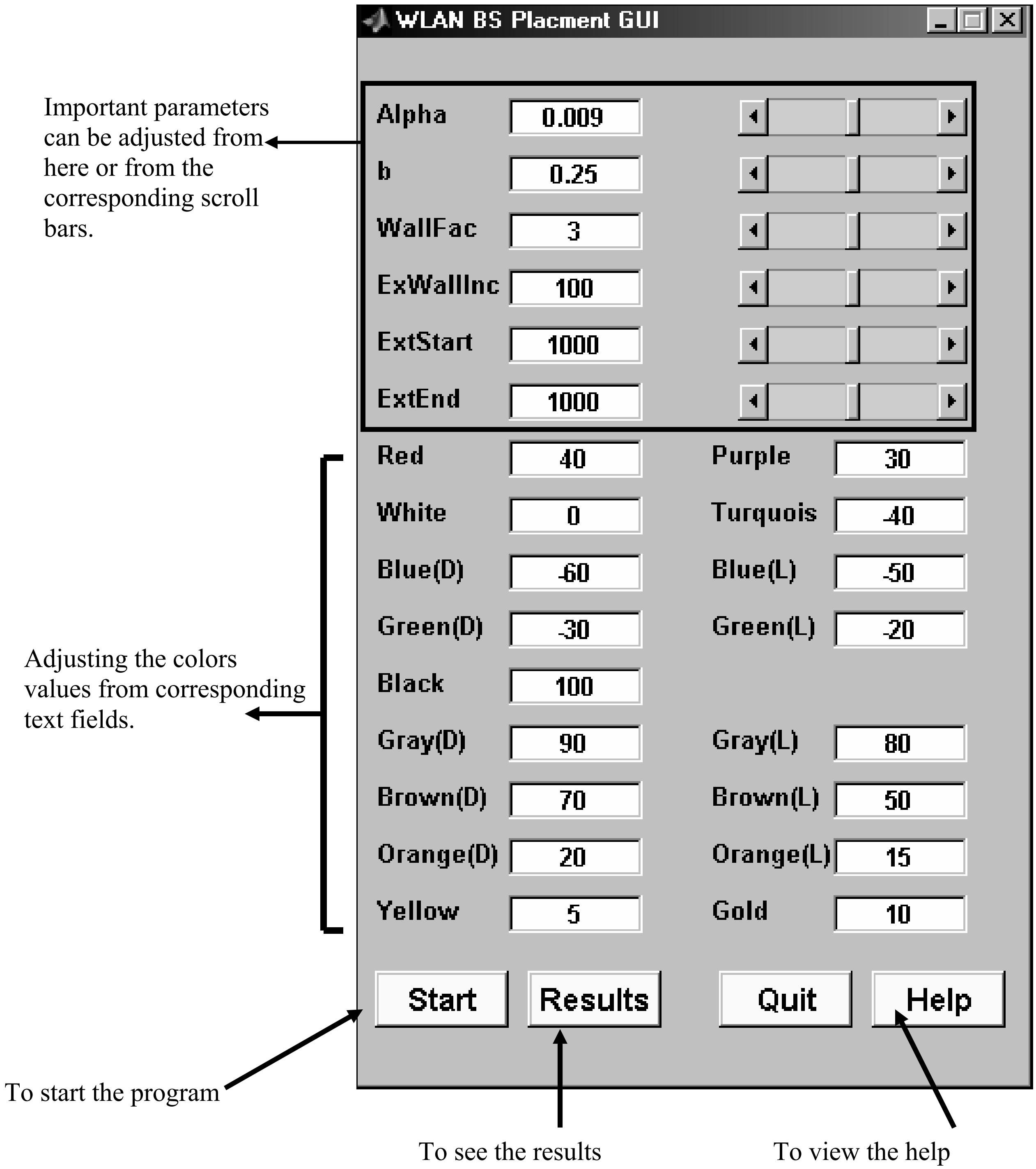


Figure 5.4: Graphical User Interface (GUI)

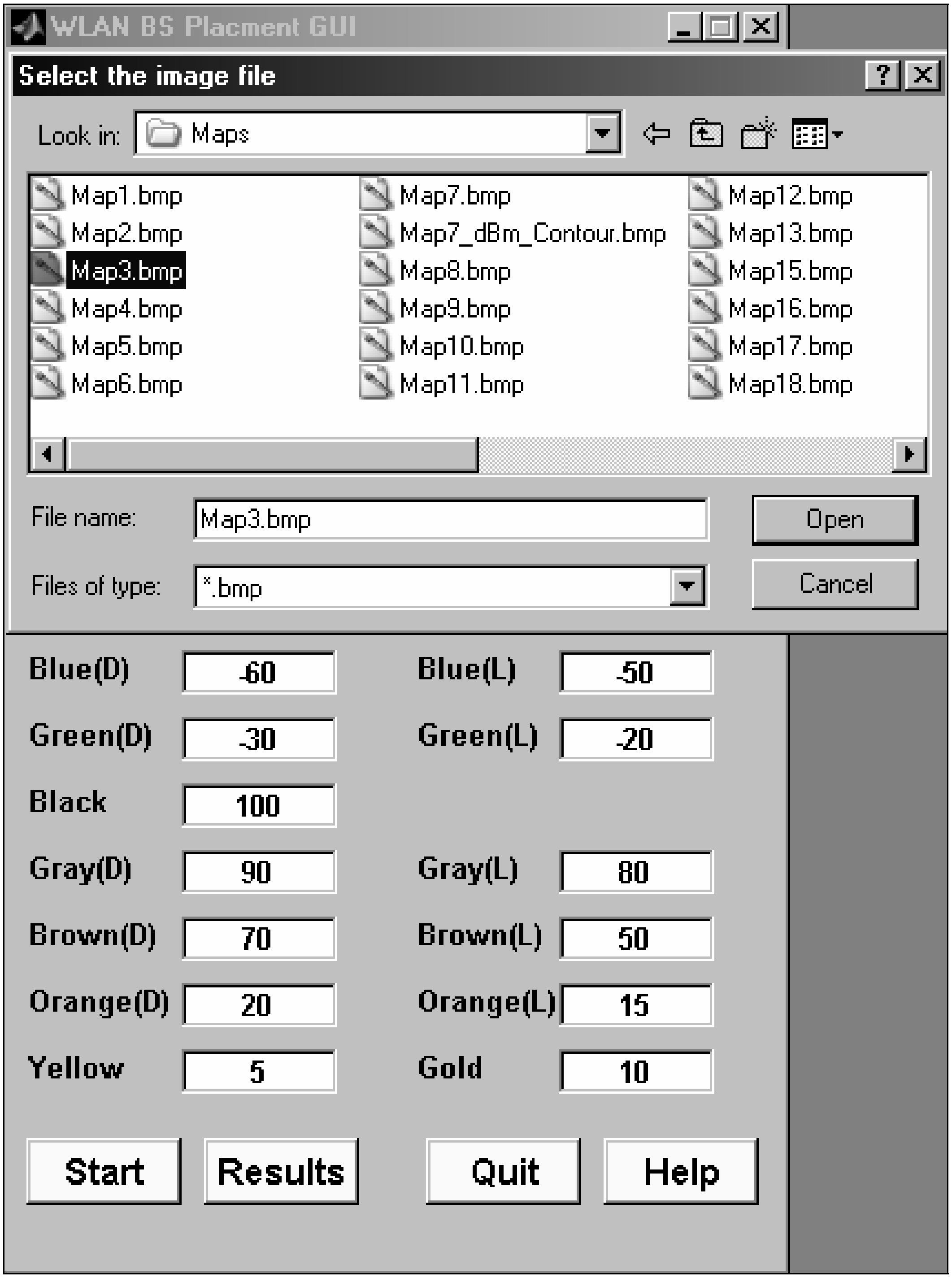


Figure 5.5: Selecting a Map in GUI

2- Data Processing:

- The algorithm will compute the power contribution of every point on the grid to its neighboring points in case it is chosen as AP location. (Demand pattern will be under consideration). In other words, for each point on the current power pattern $P_{n-l,}$ the matrix A is centered at that point and dot-multiplied with the intersecting sector of P_{n-l} .
- The multiplication values are then summed up and the answer is stored at the corresponding point in Y_n.
- This convolution process is repeated for all other points in P_{n-l} .
- Then, the point that delivers the minimum power contribution is chosen as a new AP location which means coordinates that correspond to the minimum value of the matrix Y_n are then chosen as the location of the n^{th} AP. (see 4.2)
- This process will guarantee that the new AP will be located furthest away from previously assigned APs.
- Penalty Frame is one more process to avoid placing the APs on the boundaries, by augmenting one frame of high positive values around the demand matrix F will be generated, see Figure 4.8. In this figure we show the penalty frame which acts as a repellent magnet that pushes placing the APs away from the boundaries. The optimal frame value is usually a positive number that depends on the size of the matrices A and F and their contents.
- Once a new AP location is chosen, matrix X_n is constructed from (4.3).
- After placing each AP the power matrix P is updated from (3.11) and (3.12) and the attenuation effect due to any neighboring walls will be considered.

- The algorithm stops when the minimum power inside the whole region is greater than the power threshold α. In other words, $p_{min} > \alpha$.

3- Output Results:

In this part we describe the output format in more details.

- The algorithm will return the following (see Figure 5.6):
  - The total number of APs *N*.
  - APs Locations with their *(x,y)* coordinates.
  - The minimum power value p_{min} achieved.
  - Total processing time in sec.
  - If there is more than one optimal solution, the program will recommend one of them; solution that maximizes the p_{min} is chosen as illustrated. The maximizing here means that more power is delivered to each point.
  - The final location of AP will be shown on the original map and that can be seen in Figure 5.7 with the AP number at the centre with bright color.
- The algorithm also computes the *Percentage Coverage (PC)* for each of the APs as it assigns them one-by-one. Figure 5.8 shows as illustration of the PC. In this illustration, the first AP covered 35.72% of the total area. The second AP covered 20.82% while the third and the fourth APs covered 40.93% and 2.52% respectively.

```
AP_Locations_05-Oct-2006_14_46_23_(Map7.bmp).txt - Notepad
File  Edit  Format  View  Help
==========================================================
Solutions Details for the AP Placement Problem for Map7.bmp
==========================================================

initial Information:
--------------------

Demand Matrix original size = 320 x 525 x  3
Demand Matrix F size        =  45 x  75
Reduce Factor was used      =   7
Penalty Frame Start         = 500
Penalty Frame End           = 500

Start Time = 2006-10- 5 14:46:23
===============================================

*** Solution   1  *****
----------------------------------------
General Tot. Num. Req. of AP (inc zero cov AP) =   4

Main Tot. Num. Req. of AP (exc zero cov AP) =   4

Penalty value was assigned =    500

 AP_No    APC      PC      X      Y
 -----    ---      ---    ---    ---
  1     35.72    35.72    9     68
  2     56.55    20.82   39     69
  3     97.48    40.93   27     13
  4    100.00     2.52   10     13
****************************************


Total No. of AP in all trails =      4
----------------------------------------
The optimal Solution that we suggest for your problem is   1
----------------------------------------
The minimum power is Pmin = 0.029358
----------------------------------------
Total Processing Start Time = 6.781 sec
----------------------------------------
End Time = 2006- 10- 5 14:46:30

*********************************************************
****************** End of the File **********************
*********************************************************
```

Figure 5.6: Snapshot from the Final Output Results File

Figure 5.7: Final AP locations in the Given Map

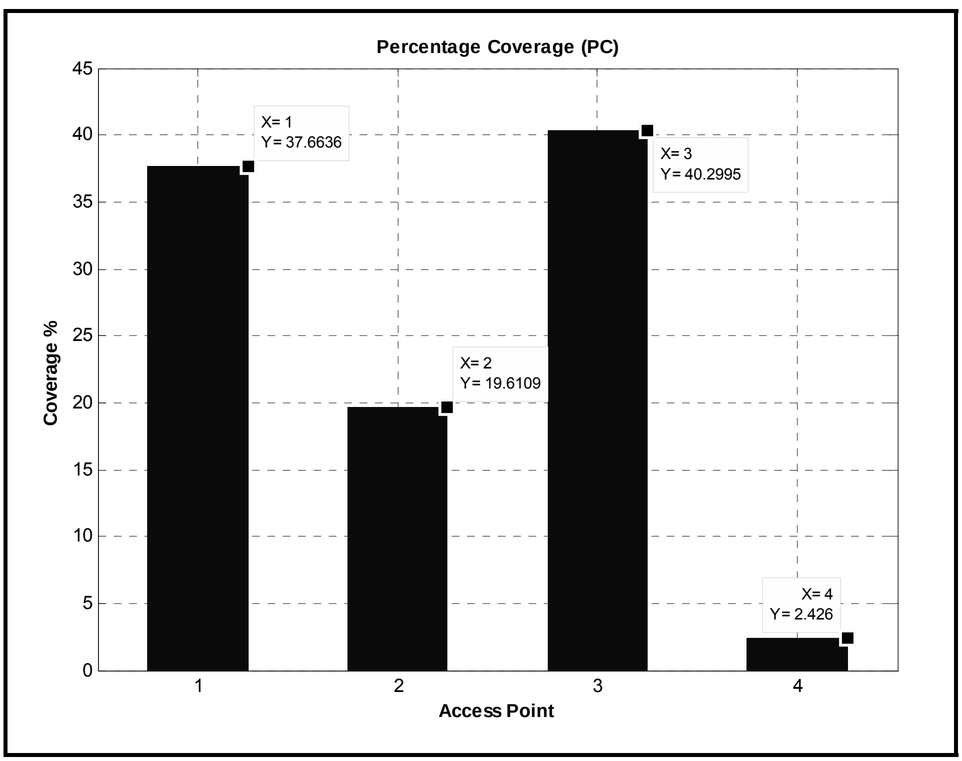


Figure 5.8: Percentage Coverage (PC) for Each AP

- The code also computes the *Accumulative Percentage Coverage (APC)* as illustrated in Figure 5.9. In this example, the first bar was showing 35.72%. Then, it increased to 56.55% that comes from (PC_1 + PC_2) and APC_3 = 97.48% which comes from (PC_1+PC_2+PC_3). Finally, the APC_4 = 100% which means we have covered all required points in the map.

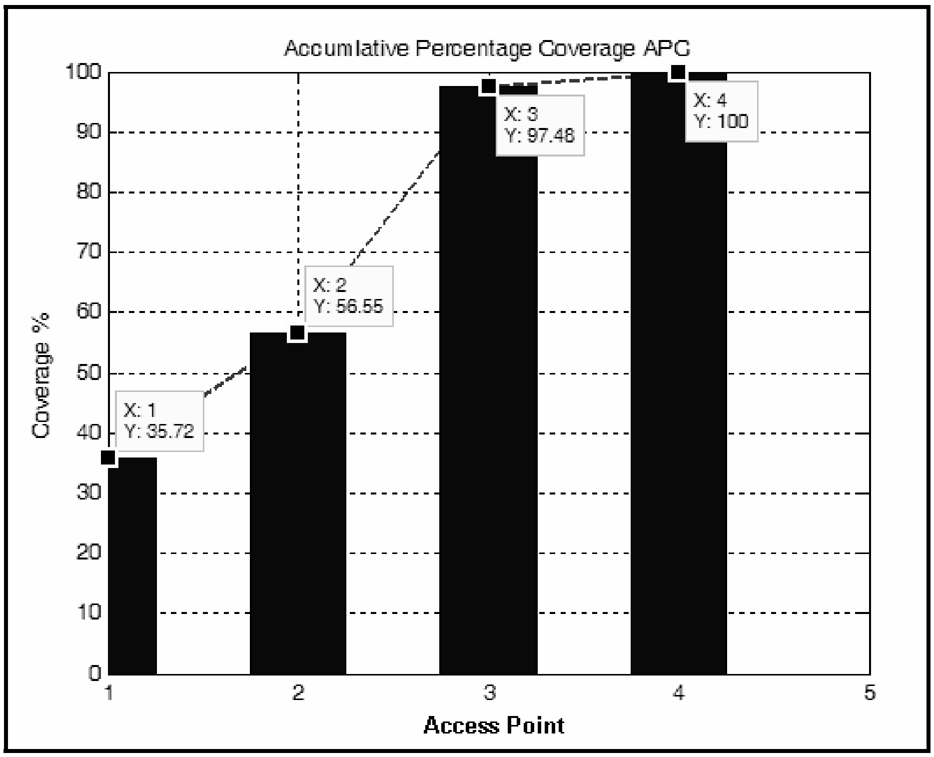


Figure 5.9: Accumulative Percentage Coverage (APC) for Each AP

- In case more penalty frame values are tried, the program can show all trials results in terms of *PC* and *APC* in one figure after showing them one by one separately. That will make the comparison job easier for the planner to view all solutions in one shot. Figure 5.10 shows a quick comparison between all trials conducted in the test in terms of *PC* and Figure 5.11 shows a quick comparison between all trials conducted in the test in terms *APC* when we tried several penalty frame values in one of the given maps. Each bar represents the coverage for AP in order in that particular set because we have 6 sets corresponding to 6 trials and 4 bars representing 4 APs. So, the first bar for AP_1 in the first set, second bar for the AP_2 in the second set and so on.

- Figure 5.12 shows a trend of the number of APs with a new penalty frame that is greater than the previous, every new trial. This brings back again the relation between the penalty frame value and the number of APs. As the value of penalty increasing, the locations of APs will be pushed toward the centre of the map as much as possible. So, each AP will cover more from the map itself and that of course reduce the number of required APs as shown in Figure 5.12. However, this value shall not go for very large positive values because after $f = 10^4$ the required effect will not be feasible.

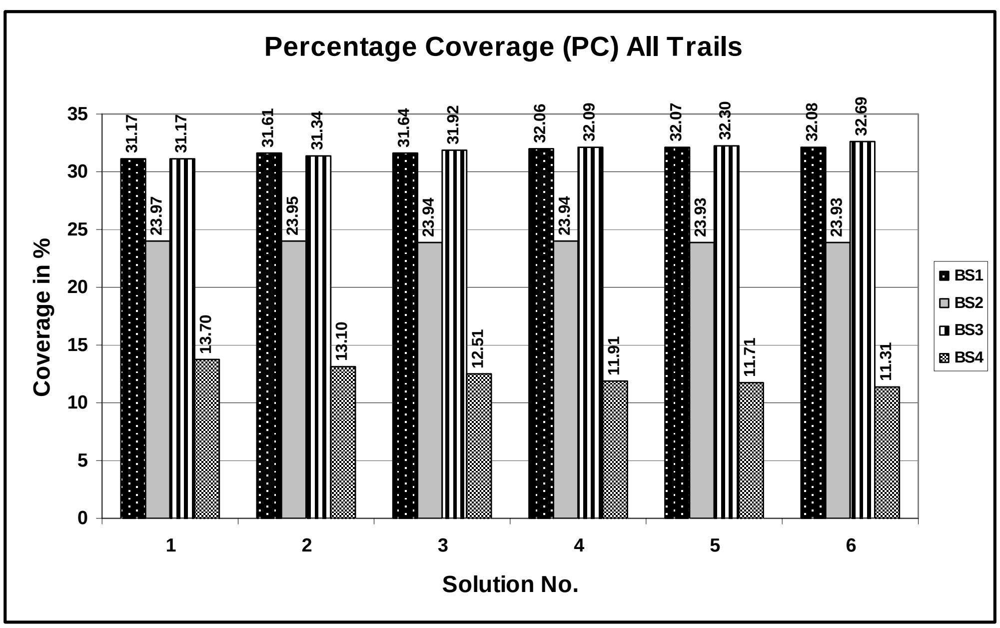


Figure 5.10: Percentage Coverage (PC) for All Trials

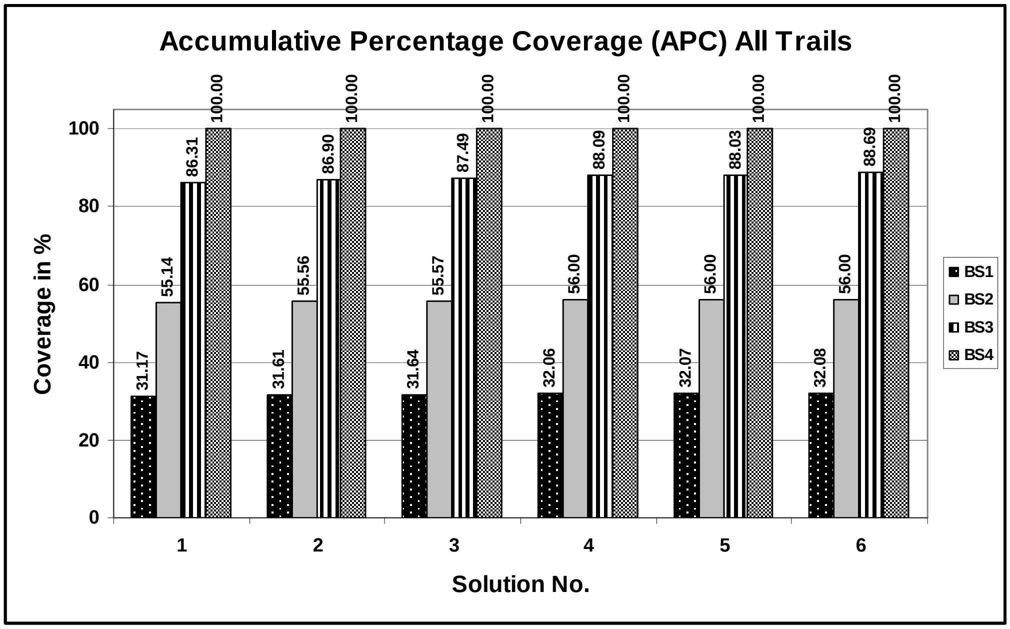


Figure 5.11: Accumulative Percentage Coverage (APC) for All Trials

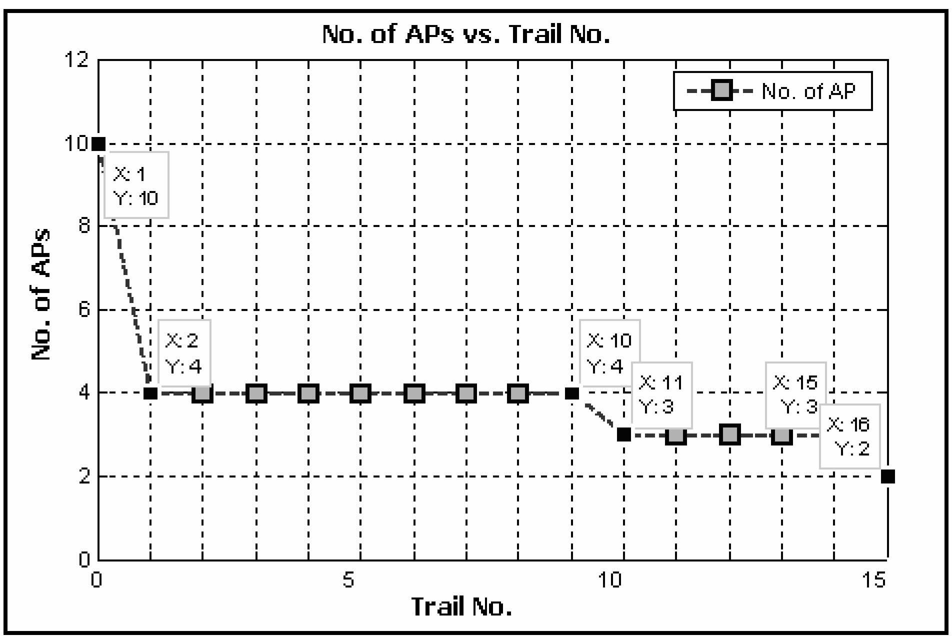


Figure 5.12: No. of APs Trend in each Trial

5.4 New Scheme to Determine the Signal Power Attenuation

5.4.1 Overview

The critical part in assigning the APs locations for indoor environment is how to simulate the signal attenuation when it passes through different types of walls. Usually, there are different types of walls in terms of materials, thickness and locations inside buildings. That will lead to several attenuation factors.

In this work, a new scheme was developed in addition to the APs allocation algorithm. It will calculate the attenuation due to the signal passing through walls. This scheme is divided into two procedures or methods:

(1) Walls Determination

(2) Signal Attenuation Calculations

In the following sections we will describe the above items in detail. This scheme has been developed to be used instead of Ray Tracing. It will check all grid points not like Ray Tracing that will skip many points in the grid depending on the search angle.

5.4.2 Walls Determination

The purpose of this scheme is to search for start of vertical, horizontal and oblique walls and store their information in special array that will keep the walls information. This information represents the start and end of the stored walls including the thickness of these walls (see example in Figure 5.13). This scheme will find these details based on the colors comparisons which are defined initially in the code. In other words, the stored information can be listed as follows:

1- Wall Start Point Coordinates (x_1, y_1).

2- Wall End Point Coordinates (x_n, y_n).

3- Wall type (horizontal, vertical or oblique).

4- Wall thickness.

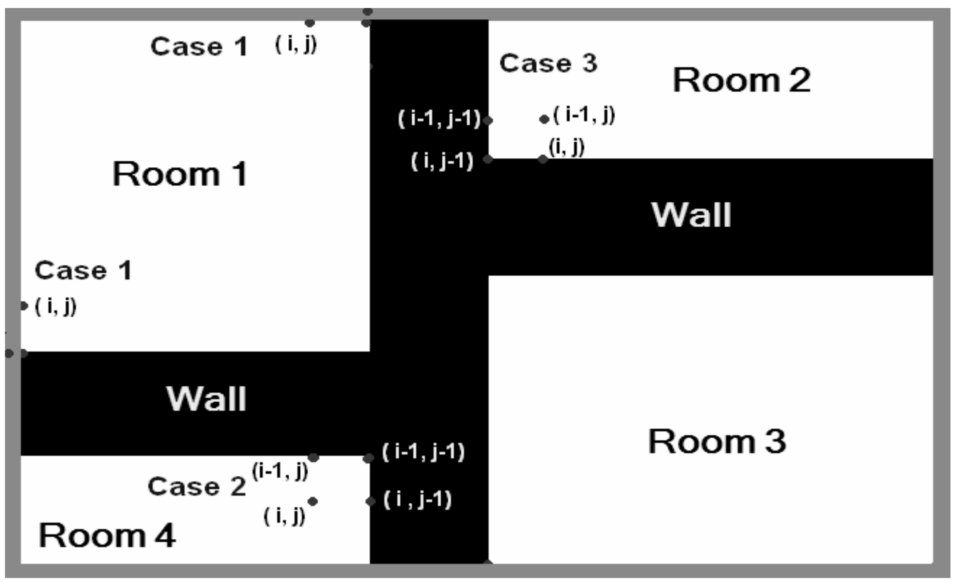


Figure 5.13: Walls Determination

5.4.3 Signal Attenuation Calculation

After finding all necessary information about the walls in the map, some calculations are made to simulate the attenuation of the signals when it passes through walls. In other words, the scheme is calculate the pathloss model. Based on the wall type and thickness the attenuation factor will affect the signals.

The following steps will be applied in parallel with placing an AP in the desired location, to consider the attenuation due to these walls:

1- The map will be divided into four regions and the centre will be the point chosen as AP location as explained in Figure 5.14.

2- From the chosen centre, the four regions will be checked if any of the region's point is behind the wall even if there are several walls after each other.

3- If the answer is YES, it will check the direction of this wall.

4- Then, the scheme will start checking the wall thickness and the attenuation factor will be selected.

5- Points located behind that wall, will be attenuated according to that attenuation factor.

6- The above steps will be repeated for every new AP until the allocation algorithm stops.

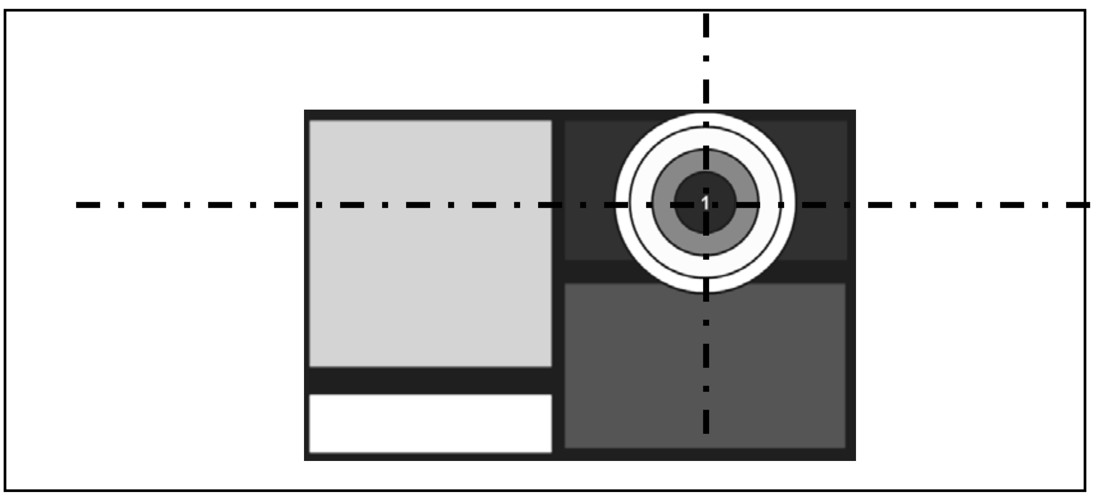


Figure 5.14: Dividing the Map Into Regions

The following map in Figure 5.15 will show a simple floor layout with an AP allocated. The contour of this AP was demonstrated in Figure 5.16 as an example of signal attenuation after applying the new scheme in 5.4.3.

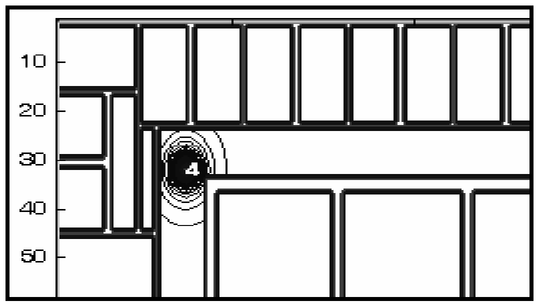


Figure 5.15: Example of Floor layout

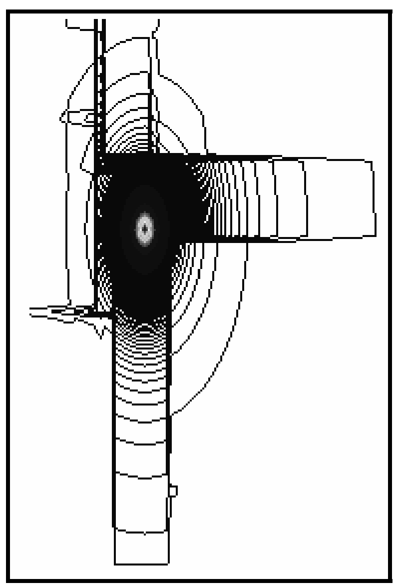


Figure 5.16: Signal Attenuation for AP

5.5 Numerical Results

In this section, the proposed solution approach will be demonstrated through several numerical examples. In the following, a list of examples and their results will be discussed.

- **Example 1:** A simple map consisting of two areas where the first area is in Blue Color which means high demand (as per Table 4.3) and the second area is in Red Color corresponding to no-demand (avoid). As expected, the algorithm has placed only one AP in the demand area and ignores the red area. Figure 5.17 shows the given map and Figure 5.18 shows the AP location in the map. Figure 5.19 shows the *PC* for that single AP and it shows also the *APC* value which is 100% which means that one AP was enough to cover the demand area.

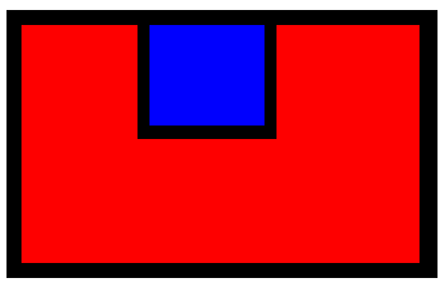


Figure 5.17: Map of Example 1

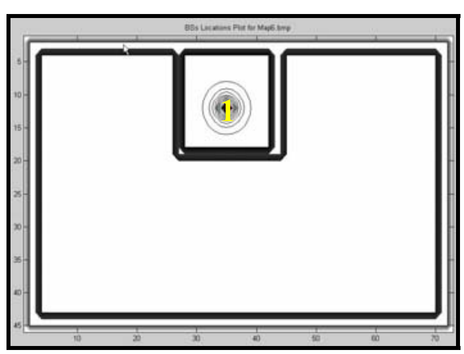


Figure 5.18: The Final Location of AP in the Map of Example 1

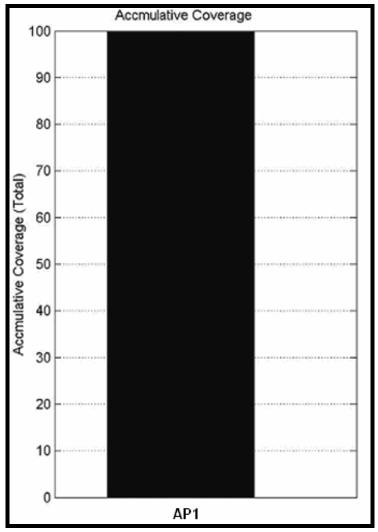


Figure 5.19: APC and PC for the AP in the Map of Example 1

- **Example 2:** In this example, the used map is shown in Figure 5.20. This simple map is composed of four main areas: the first one is with Dark Blue Color (Highest Demand Priority, scale -60 as per Table 4.3) , second area is with Light Green Color (High Demand Priority , scale -20), third area with White Color (Normal Demand , 0 scale) and the 4th area is with Red Color representing prohibited area (avoid , scale is +40).

  Logically the first AP shall be placed first in the highest demand area then next high demand area until the whole demand requirements are achieved. Figure 5.21 shows the resulting AP placement on the map. The first AP was placed on the blue area as expected and it contributes to 67.81% of the coverage while the second AP was placed in the green area and it covers 32.19%. The optimal penalty frame in this case is 1500 and the resulting p_{min} is 0.07326 which is greater than the threshold $\alpha = 0.01$ and the total processing time is 1.883 sec.

The original map size is 142 × 258 pixels (3.76 × 6.83 cm). For the *PC* and *APC* are shown in figures 5.22 and 5.23, respectively.

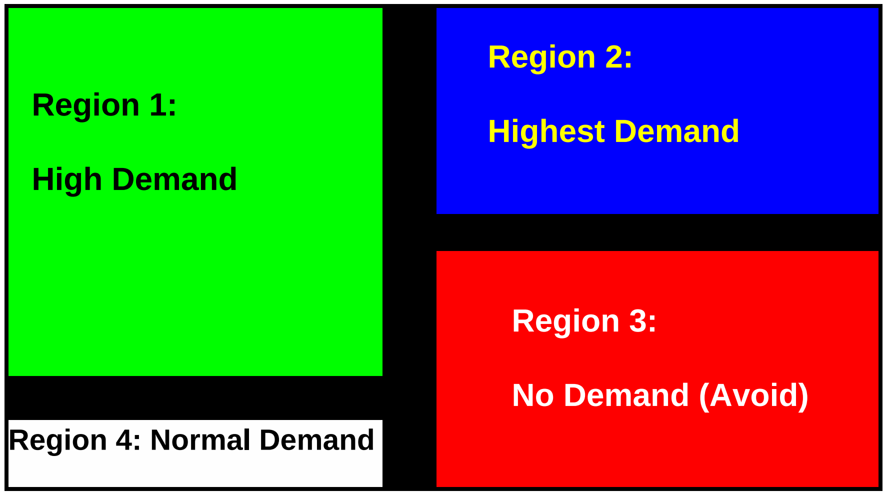


Figure 5.20: Map of Example 2

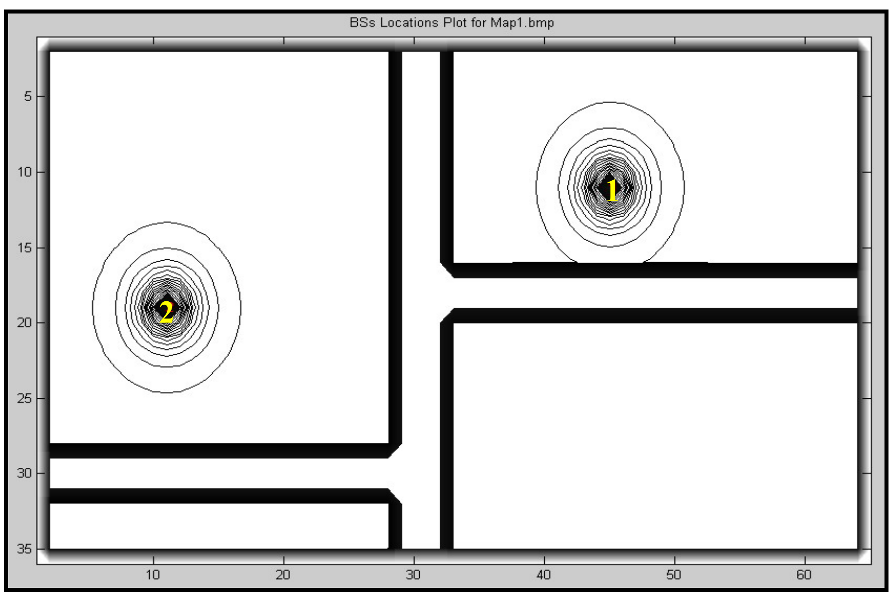


Figure 5.21: AP locations for Map of Example 2

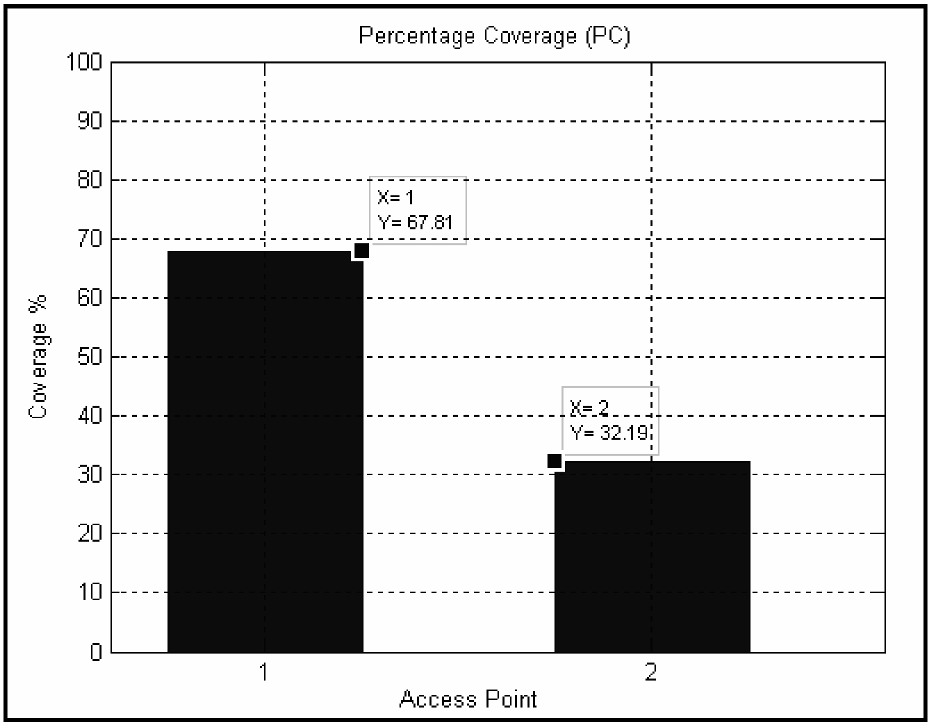


Figure 5.22: PC for each AP in the Map of Example 2

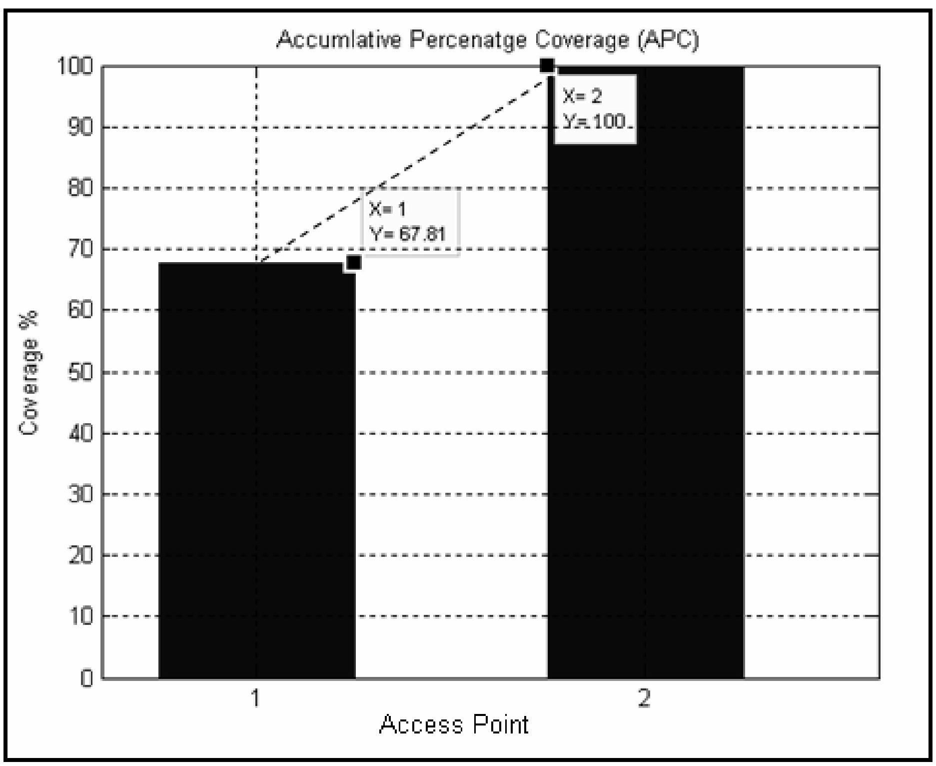


Figure 5.23: APC for the APs in the Map of Example 2

If we go back to the penalty frame effect, the provided map in Example 2 will have a different solution if we don't apply a penalty frame principle. Instead of 2 APs we will have 10 APs when there is no penalty frame because the APs will move towards the edges and then you need more APs to cover the required area. The following Figure 5.24 will show that as we increase the penalty frame value, the locations of AP will move toward the inside of the map and their coverage will increase because no coverage will be lost outside of the map. Hence, the number of AP will be reduced but this reduction will stop at a certain level.

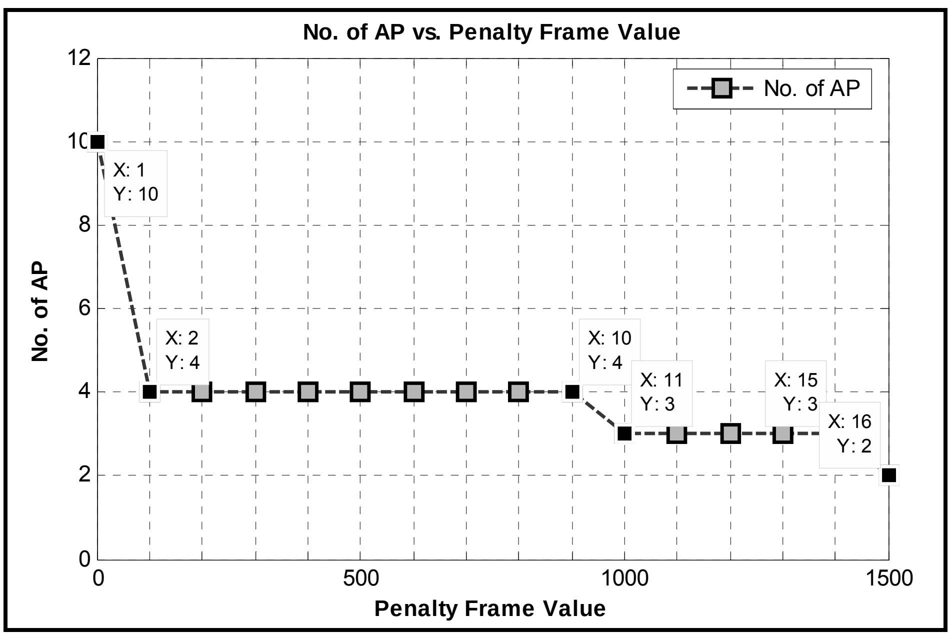


Figure 5.24: Effect of Penalty Frame Value on the No. of AP

- **Example 3:** Figure 5.25 shows a more involved demand patterns. We refer back to Table 4.3 to determine the scales which are used to construct the demand matrix *F*. The algorithm has placed the first AP at the top area where there is a large demand, a blue followed by two green areas, and it contributes to 35.72% coverage. The second AP was placed in the next blue area, which is smaller than the first blue area, and it covers 20.82%. The third AP is placed far from the previous APs and it covers 40.93% and by this distribution we reach 97.48% of the total coverage of the map which could be enough to stop at this stage. However, the algorithm provided one final AP with 2.52% coverage to achieve 100% with p_{min} = 0.02935. The placement, *PC* and *APC* are shown in Figure 5.26, 5.27 and 5.28, respectively.

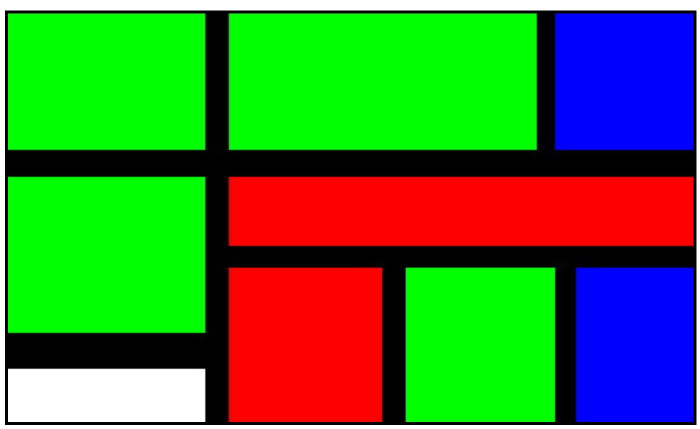


Figure 5.25: Map of Example 3

Figure 5.26: APs Locations on Map of Example 3

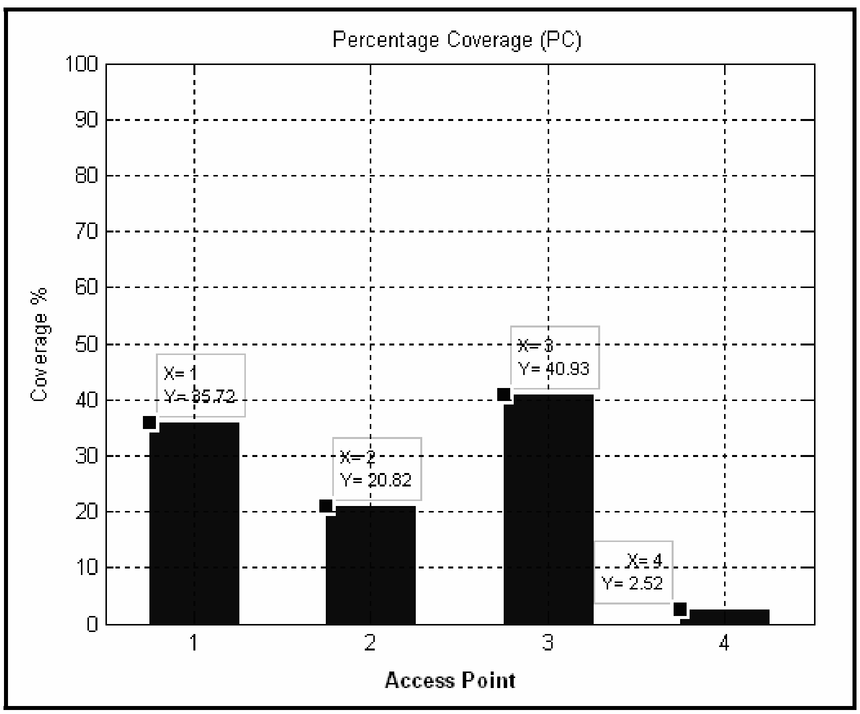


Figure 5.27: PC for each AP in Map of Example 3

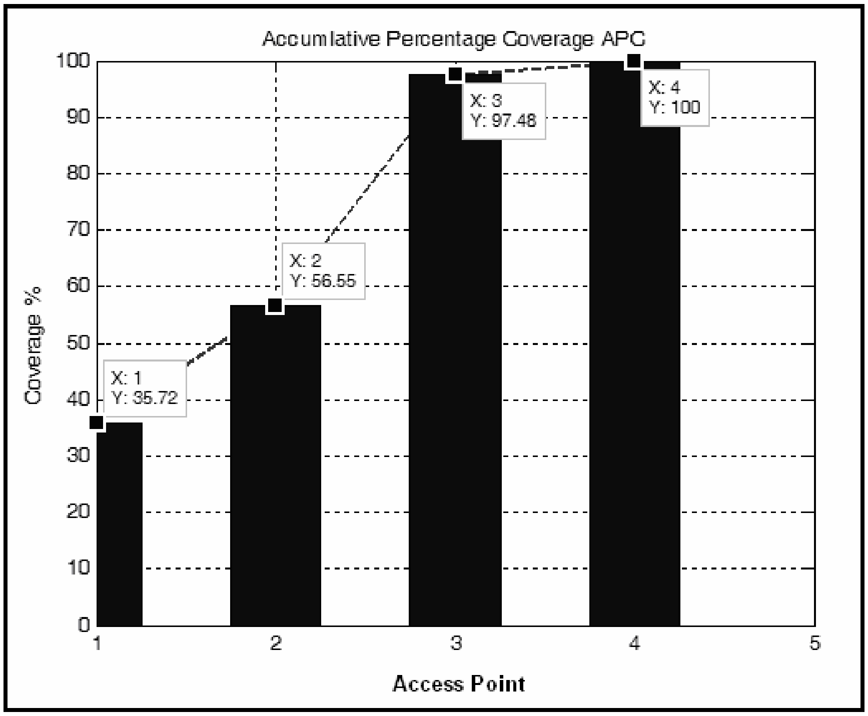


Figure 5.28: APC after placing each AP in Map of Example 3

The Figure 5.29 shows an example on the effect of choosing the penalty frame value (*f*) on the AP coverage. As the *f* increased, the location of AP will be pushed away from the borders. That will reduce the lost coverage outside map borders.

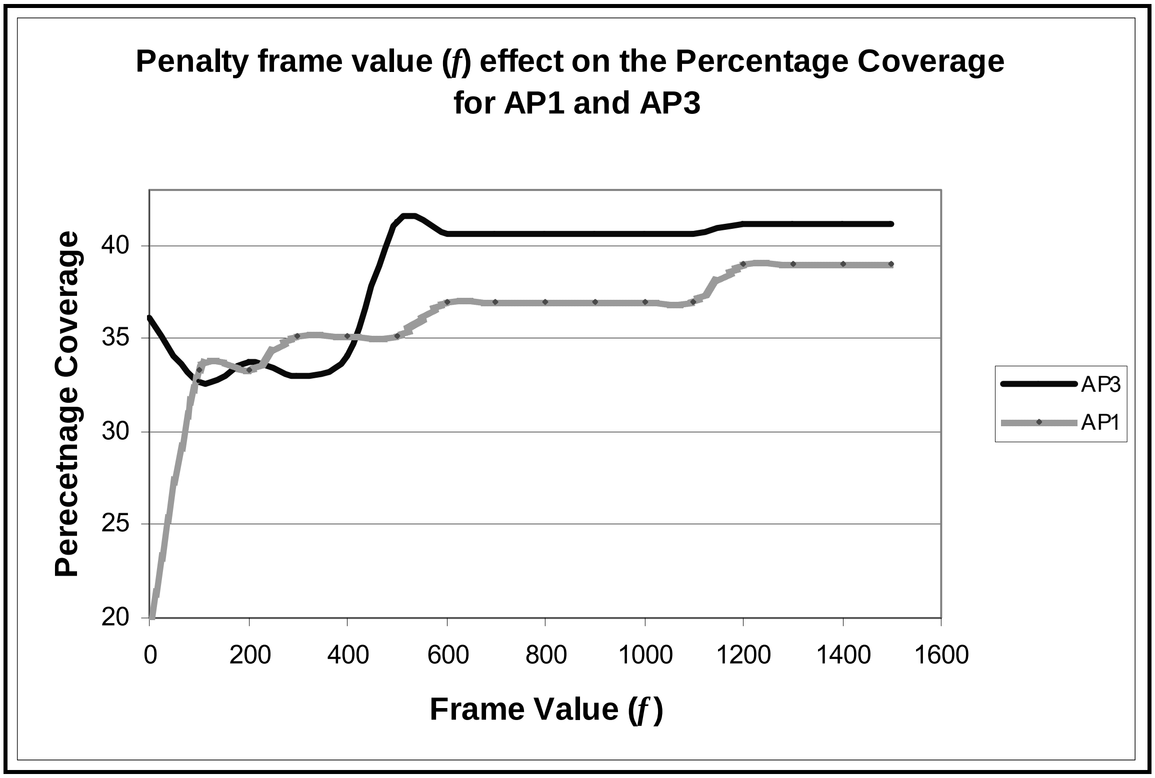


Figure 5.29: APs Locations Analysis

- **Example 4:** In this example we have a different map style in which we have some oblique walls. The map is shown in Figure 5.30 and it has two very high demand regions colored with blue and one high demand region colored by green. There is also, one normal demand region with white color. Finally, the last region is a prohibited region colored by red. The program has assigned 4 APs to cover the whole map 100% and put in mind that 98.09% of the coverage was achieved after the third AP was placed. Figure 5.31 shows us these locations in the map and as expected the first location was in the highest demand region with 56.71% and also the second one is in the next blue region with 26.77% of coverage. Together they cover 83.48% which is an excellent coverage with just two iterations. The third

AP covers 14.61% and by this we could reach up to 98.01% of the total coverage. In both Figures 5.32 and 5.33 we show all *PC* and *APC* values and the minimum power (p_{min}) was 0.02896 which is above the threshold α = 0.01.

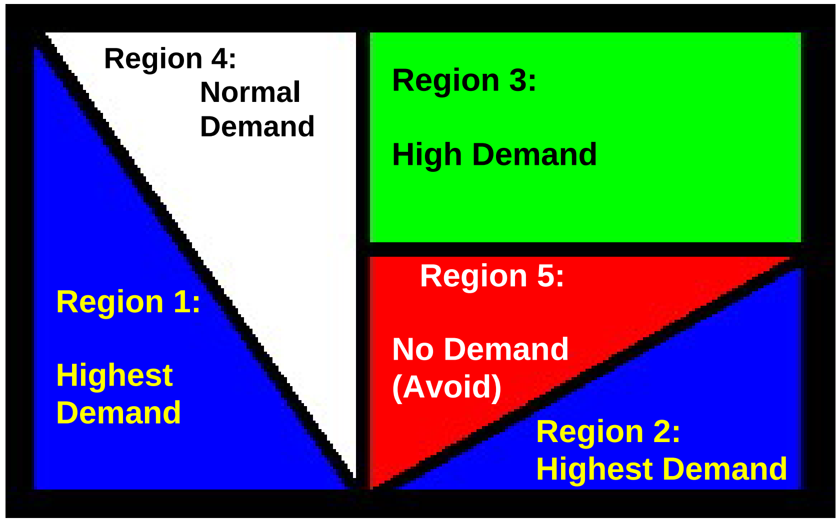


Figure 5.30: Map of Example 4

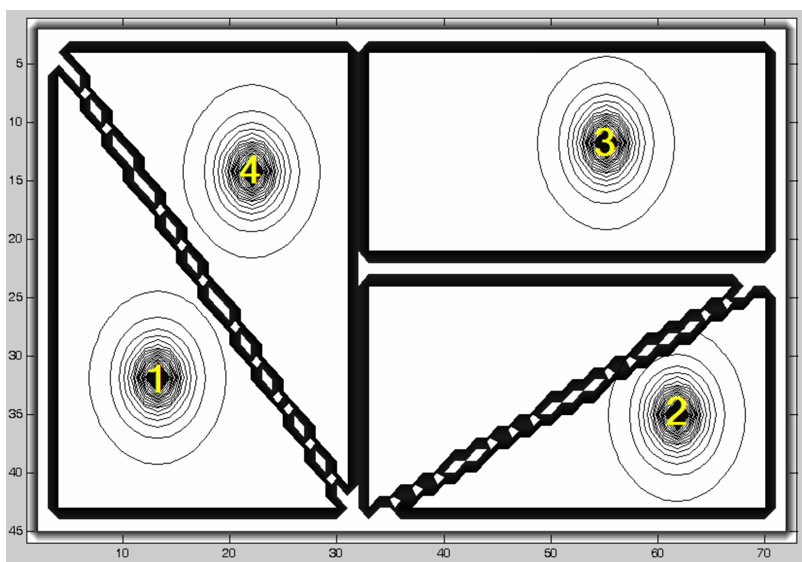


Figure 5.31: AP Location for Map of Example 4

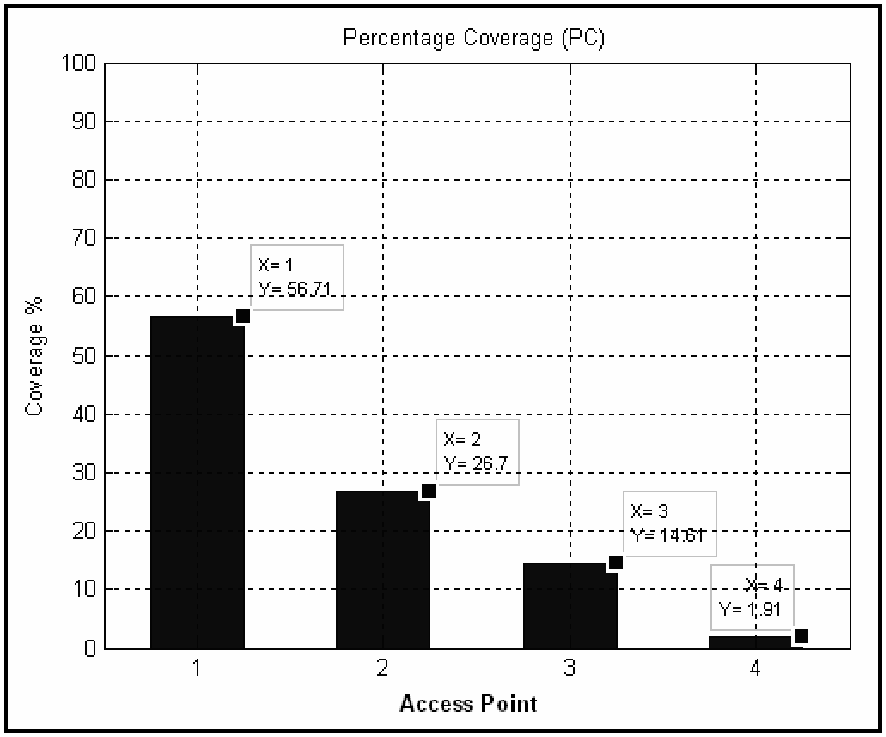


Figure 5.32: PC Values for Each AP in Map of Example 4

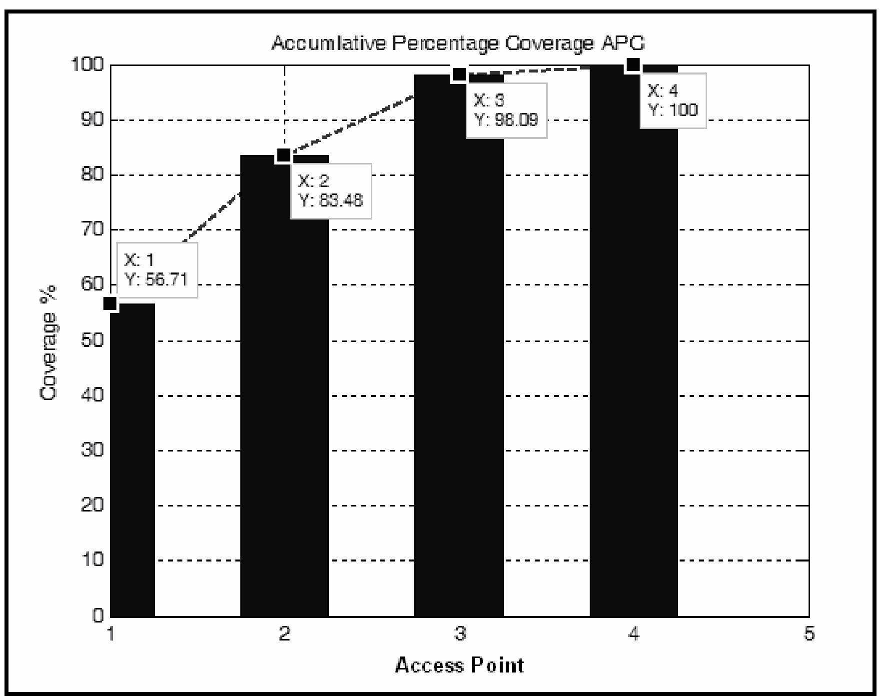


Figure 5.33: APC Values for Each AP in Map of Example 4

5.6 Summary

In this chapter, the proposed solution approach was described and all its phases were explained in detail. The program GUI was also introduced. Moreover, the colors standards which were used by the proposed solution were discussed in detail. After that, some examples were given to illustrate the implementation of the solution approach. Moreover, we notice from all the examples that as expected, the first AP is always located in the blue region (corresponding to very high demand). Then the program will look to the next high demand region such as the green region in order to cover it. Also, the algorithm avoided the placement of any AP in the red region (corresponding to no-demand or avoid region). The minimum power return by the algorithm, $p_{min,}$ was always just above the required power threshold which is given in the program as an input.

CHAPTER 6

SOLUTION VERIFICATION AND COMPLEXITY ANALYSIS

6.1 Verification of the Solution

In section 5.5 we tried the proposed solution approach on simple problems where solutions can be readily determined. In this section, we further supported this finding by comparing the results of the proposed algorithm with that of known results. More specifically, the results of the proposed algorithm are compared in this section with that of Exhaustive Search, Genetic Algorithm and Log Distance pathloss model.

6.1.1 Exhaustive Search

An exhaustive search was done on site map with grid size (16 × 17). All possible combinations of two APs were tried. The search will challenge the proposed algorithm by trying to find one of the following:

- Lower number of APs that will meet the coverage requirements
- Different locations of the same number of APs that provide better power coverage (higher p_{min}).

The exhaustive search was applied on the map of Figure 6.1 of size 16 × 17 which produces a total of 36,856 trials. Those are the results of $\binom{272}{2}$ combinations. The exhaustive search lasted 3 minutes to produce the result.

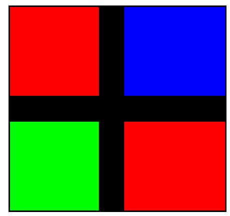


Figure 6.1 : Map of Exhaustive Search

The same map was used by the proposed algorithm. The locations and the coverage of the base APs were exactly matching. Table 6.1 shows the results of exhaustive search and that by proposed approach where the number of iterations required by the proposed algorithm was only two. That means we can get the same results as exhaustive search after two iterations only and 0.1 sec compared to 3 minutes. Figure 6.2 shows the resulting contour plots for both methods.

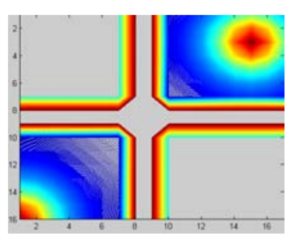


Figure 6.2: APs Locations

TABLE 6.1: Exhaustive Search vs. Proposed Approach

	Exhaustive Search				Proposed Algorithm			
	x	y	PC	APC	x	y	PC	APC
AP1	3	15	54.286 %	54.286 %	3	15	54.286 %	54.286 %
AP2	16	1	45.714 %	100%	16	1	45.714 %	100%

6.1.2 Genetic Algorithm (GA)

In another experiment, we compared the performance of the proposed algorithm to that of the well-known Genetic Algorithm (GA) optimization technique. In this case, we consider 7 cells coverage as shown in Figure 6.3. To cover the given map using the GA it was necessary to perform 1000 generations of solutions until it finally converges to 99.8% coverage [18, 21]. In contrast, in Figure 6.4 the proposed algorithm needed only 7 iterations to cover the same map. The proposed algorithm resulted in 100% coverage within 20 sec.

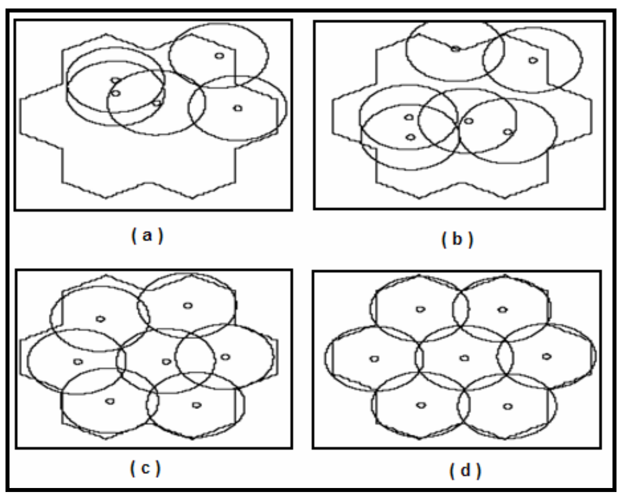


Figure 6.3: Genetic Algorithm Example for APs placement on generation (K=7, t=1). (a) Initial generation (51.84% coverage). (b) After 1st generation (63.15% coverage). (c) After 100th generation (94.98 coverage). (d) After 1000th generation (99.80% coverage).

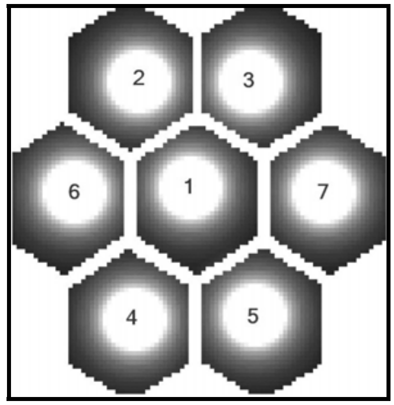


Figure 6.4: Proposed Solution Output on Same GA Example

6.1.3 Log Distance Model

An experiment was performed using a subset of the deployed wireless infrastructure in the computer Science building at Stanford University [25]. The indoor measurements were done in the fourth floor, as depicted in Figure 6.5. Around 41 locations were sampled within a 66m × 24m area and they are shown as red circles in Figure 6.5. From these, 13 were located inside offices (5.2m × 3.2m), 15 inside conference rooms (at least 8m × 4.7m), and 13 in corridors. Finally, a total of four APs were employed, their locations being represented by blue triangles in Figure 6.5. For each of the 41 locations shown in Figure 6.5, the quality of the signal relative to each AP was measured. In total, 146 AP-client associations were used, and the resulting total coverage was 98%.

In contrast, if the proposed scheme is applied, the solution is simpler and there is no need to fix 41 APs and try all their associations to end up with 146 trials. What is required is just to feed the map to the program after coloring it and the results will be ready in 9.954 seconds. The final result was 4 APs and almost in a competitive places and the p_{min} = 0.009725 (See Figure 6.6). The resulting coverage is 100%.

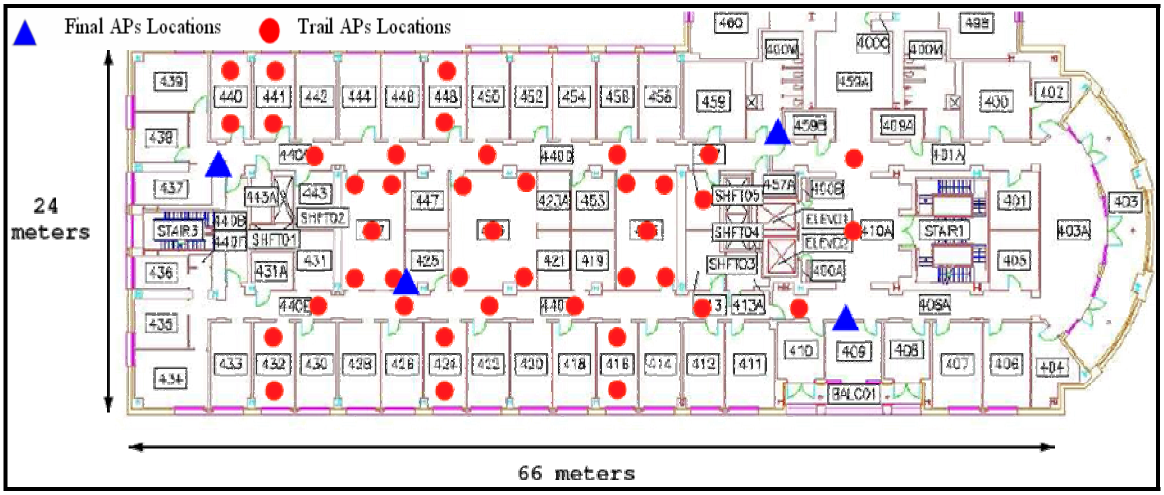


Figure 6.5:Example of Academic Building Map [25]

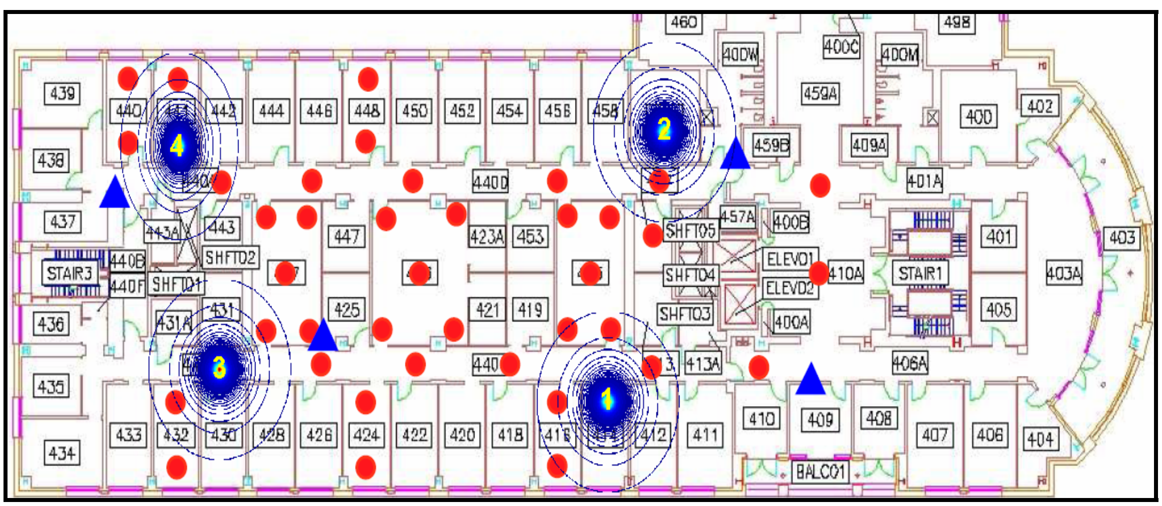


Figure 6.6: Academic Building Covered by AP with the Proposed Scheme

6.2 Complexity of the Proposed Algorithm

One of the major advantageous of the proposed algorithm is that it can be implemented very efficiently, thanks to using the convolution as the core building block. As well known, convolution can be implemented using different methods. For example, convolution theorem can be used to reduce the number of complex operations from Ő(m^2) to just Ő($m\log m$).

From the previous sections, the computation complexity of the proposed scheme has an outer loop as well as an inner loop. The outer loop searches for the optimal penalty frame value. The inner loop searches for the optimal number of APs and their locations by implementing the algorithm in the Figure 4.1. For the outer loop, a simple line search is enough to find the optimal scalar frame penalty value. The search is limited to integer values between [0, 1500] and can be changed as required.

In the inner loop shown in Figure 4.1, the convolution $A \otimes P_{n-1}$ is the most expensive operation. The 2-D convolution cost m^2 multiplications where m represents the number of grid points in the map ($m = I \times J$, I = number of rows and J = number of columns). However, this number can be reduced by utilizing available efficient schemes for computing the convolution (more detail are shown in section 6.3.1). For example, the convolution theorem will reduce the number of multiplications to $m\log m$. Also, there are two more factors which will help in reducing the complexity. First, the matrix P_n usually starts with a structure of zero elements, corresponds to normal demand in matrix F. Regions with zero values can be ignored in computing the convolution. This matrix is filled up gradually with nonzero values as new APs are assigned. Second, the search space is reduced as new AP is assigned. Therefore, the number of complex operations in the convolution can be strongly reduced by ignoring the locations already meeting the coverage requirements.

6.3 Experimental Tests for Complexity

As mentioned above, convolution theorem can substantially reduce the number of multiplications in computing the 2-D convolution. To make the comparison, different methods were built to compute the 2-D convolution:

1- ***Direct Convolution*:** A time domain function which represents equation 3.9 without any code optimization. This function theoretically has a complexity of Ő(m^2). Figure 6.7 shows the simulation results for the time needed to assign one AP, together with the theoretical fit using μm^2 where $\mu = 2.88$.

2- ***FFT Based Convolution:*** This method uses the FFT and IFFT to compute the convolution. It has a complexity of Ő($m\log m$). That makes the calculations much faster than the Direct Convolution function. Figure 6.8 shows both the theoretical using $\beta m\log m$ where $\beta = 1.754 \times 10^{-5}$ and the simulation results where lower processing time can be observed.

The difference between the two functions can be shown in another way as in Figure 6.9 where different map sizes were tested for 100 iterations. Then, the average of processing time required to cover the map for each value of *m* was compared. Clearly, the FFT-based approach resulted in a substantial reduction in complexity, making the proposed approach feasible for maps with large grid size.

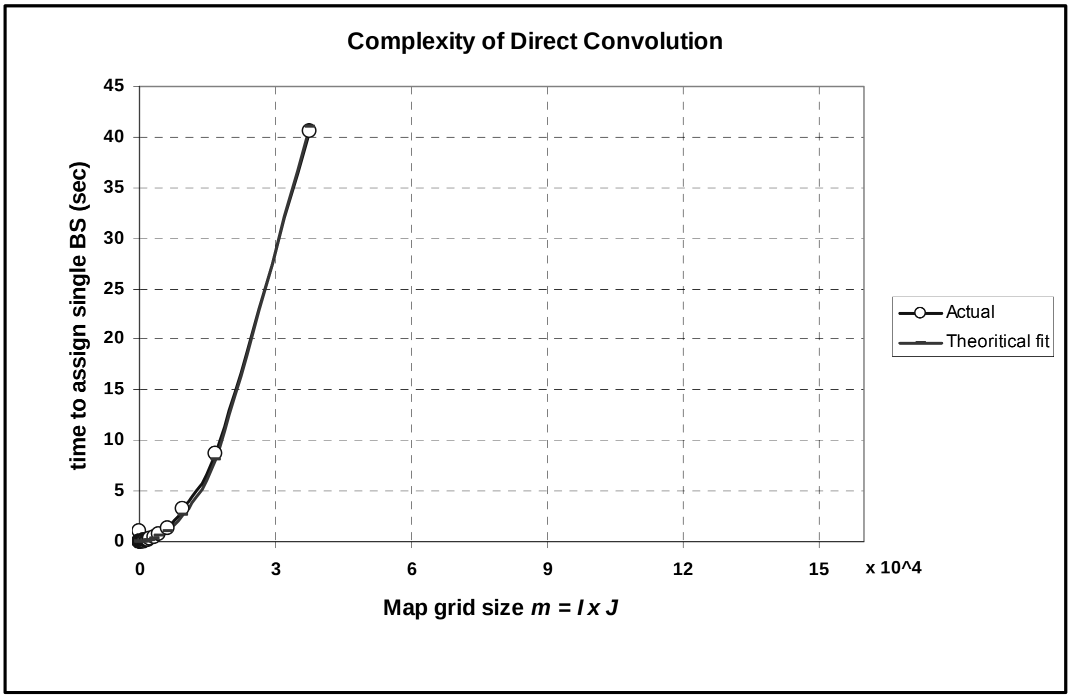


Figure 6.7: Time needed to assign single AP as a function of grid size *m* using Direct Convolution

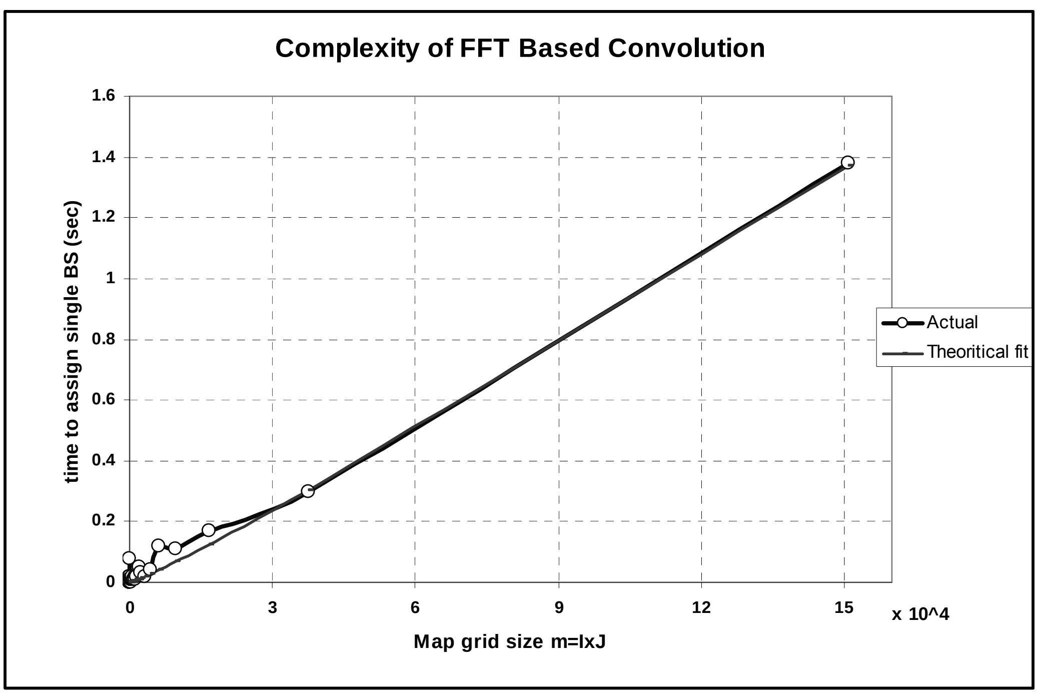


Figure 6.8: Time needed to assign single AP as a function of grid size *m* using FFT Based Convolution

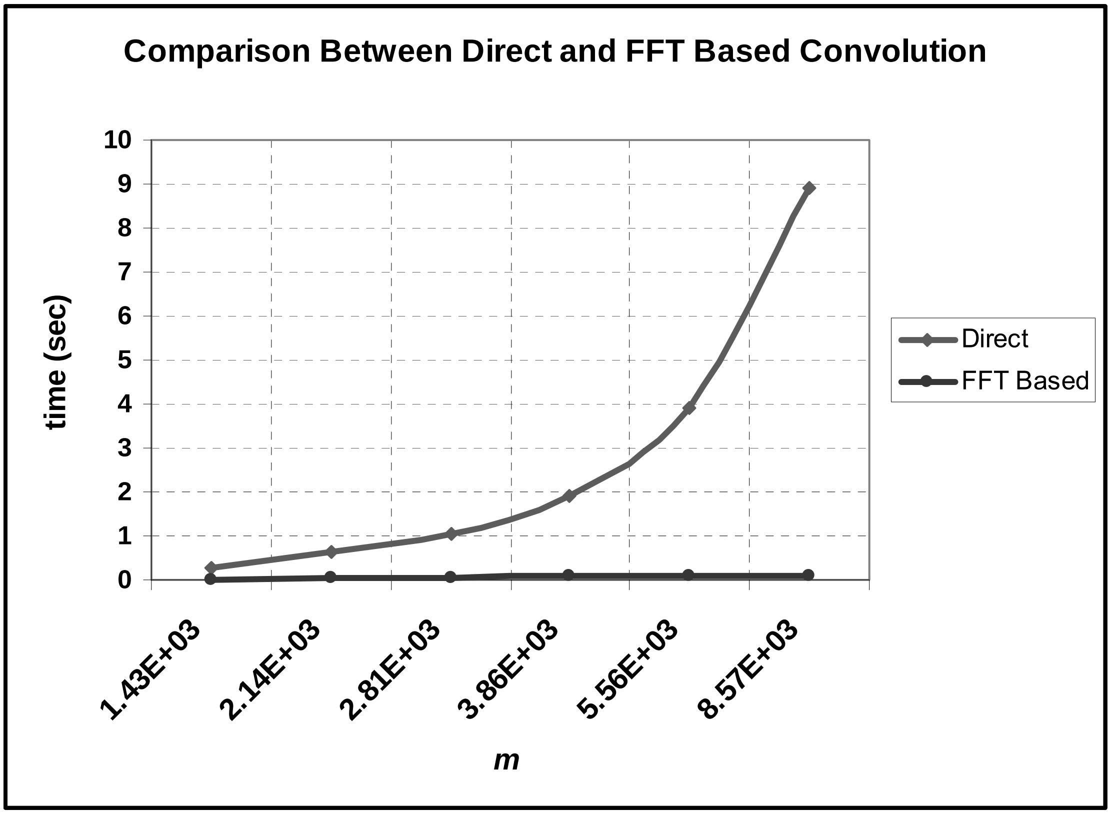


Figure 6.9: Comparison between direct and FFT-based convolution, for time needed to assign single AP as a function of grid size *m*

6.4 More Features

As we have seen in the literature review there were so many proven methods used to solve the placement problem and people are using it. In addition to what mentioned in this chapter, still there are several properties for the proposed scheme like the following.

- *Simplicity in coding:* few lines of codes are required compared to other methods like Genetic Algorithm and integer programming to model the problem.
- *Flexibility:* The proposed approach shows major flexibility in choosing arbitrary power propagation, demand patterns and output file type.
- *Variables:* Number of variables required to formulate the problem is small compared to methods like integer programming where one needs to define many constraints and variables.

CHAPTER 7

CONCLUSION

7.1 Summary

In this work we proposed a new approach to solve the placement of WLAN APs. The objective of the study is to compute the minimum number of APs and their locations that will satisfy the problem constraints such as power coverage requirement. This is done by implementing a new numerical approach based on 2-D convolution. The proposed approach provides flexibility in choosing arbitrary power propagation and coverage demand patterns. Simulations of this new approach show the efficiency and flexibility in solving the placement problem.

7.2 Future Research Directions

In this thesis, an attempt has been made to find the optimal locations for the WLAN APs for the indoor areas by using the well known 2-D convolution technique. In the following, we list some possible extensions for this work.

- The site-map can be extended to 3-D instead of 2-D.

- Other parameters, such as antenna height, direction and transmission power can be included in the optimization process.
- Frequency planning can also be optimized.
- Include more QoS parameters in the formulation.
- Take in consideration the dynamic demand requirements.

The proposed solution also can be applied in more areas for several types of applications like:

- Traffic load in Train/Tram APs inside the city.
- The Distribution of Auto Teller Machines inside hyper buildings like big shopping malls.

In general, it can be used for facility locations problem where the locations and the number of serving units need to be optimized.

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VITAE

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