# An Investigation of the Impact of Signal Strength on Wi-Fi Link Throughput through Propagation Measurement

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# Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signature: ____________________

Eric LO

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# Abstract

Wireless local area networks (WLANs) play an increasingly significant role in providing ubiquitous network services in contemporary society due to their mobility and cable free usage. It is more challenging to maintain higher throughput of WLANs than wired networks. In this dissertation, an experimental investigation of the impact of signal strength on Wi-Fi link throughput in an obstructed office environment is reported.

Due to the complexity and unpredictable nature of radio signal propagation, it is difficult to derive real and accurate signal strength and link throughput by analytical modeling and computer simulation. The received signal strength (RSS), attenuation and path loss depends on the propagation environment. The location of an access point (AP) has a significant effect on WLAN performance. An appropriate AP placement is required to obtain greater performance of WLANs. Through extensive radio propagation measurements, the results demonstrated both the relationship of signal strengths with the Wi-Fi link throughput; and optimum AP placement.

This research carried out some significant contributions. Firstly, the results revealed that not only WLAN throughput depends on RSS, but also on factors such as the distance and the obstruction between a transmitter and a receiver, and the nature of radio propagation. In addition, the experimental measurements deduced the optimum locations for AP placement in the crowded office environment. A rich database which has been developed contains RSS and throughput for a similar WLAN environment with the intent of using it for AP placement. Furthermore, two different kinds of AP configuration solutions are proposed for Wi-Fi deployment including “wireless distribution system (WDS) with AP mode” and “AP mode” with Ethernet connection in the obstructed office block. The above solutions will meet different user requirements and application behaviors. The capacity evaluation of WLAN is also discussed. Finally, some practical guidelines have been recommended for AP deployment in the obstructed office environment.

# List of Abbreviations and Notations

| | |
|---|---|
| AP: | Access Point |
| BER: | Bit Error Ratio |
| BSS: | Basic Service Set |
| CCK: | Complementary Code Keying |
| CFP: | Contention-Free Period |
| CSMA/CA: | Carrier Sense Multiple Access / Collision Avoidance |
| DCF: | Distributed Coordination Function |
| DIFS: | DCF InterFrame Space |
| DOC-CCK: | Different Orthogonal Code Sets-CCK |
| DS: | Distribution System |
| DSSS: | Direct-Sequence Spread-Spectrum |
| EIFS: | Extended InterFrame Space |
| ERP: | Extended Rate PHY |
| ESS: | Extended Service Set |
| FCC: | Federal Communication Commission |
| FHSS: | Frequency-Hopping Spread Spectrum |
| HR/DSSS: | High Rate Direct Sequence Spread Spectrum |
| IBSS: | Independent BSS |
| IR: | Infrared |
| ISM bands: | Industrial, Scientific and Medical bands |

| | |
|---|---|
| LLC: | Logical Link Control |
| LOS: | Line-of-Sight |
| MAC: | Medium Access Control |
| NLOS: | Non-Line-of-Sight |
| OFDM: | Orthogonal Frequency-Division Multiplexing |
| PBCC: | Packet Binary Convolutional Coding |
| PCF: | Point Coordination Function |
| PER | Packet Error Rate |
| PHY: | Physical Layer |
| PLCP: | Physical Layer Convergence Procedure |
| PMD: | Physical Medium Dependent |
| QoS: | Quality of Service |
| RSS(I): | Received Signal Strength (Indication) |
| RTS/CTS: | Request to Send/Clear to Send |
| RX: | Receiver |
| SINR: | Signal-to-Interference and Noise Ratio |
| SIR: | Signal-to-Interference Ratio |
| SNMP: | Simple Network Management Protocol |
| SNR: | Signal-to-Noise Ratio |
| SSID: | Service Set Identifier |
| TCP: | Transmission Control Protocol |
| TX: | Transmitter |
| UDP: | User Datagram Protocol |
| WDS: | Wireless Distribution System |
| WLAN: | Wireless Local Area Network |

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# Chapter 1

# Introduction

There has been a significant growth in the deployment of Wi-Fi (also known as IEEE 802.11) network in recent years. In particular, the number of wireless local area network (WLAN) hotspots is growing fast year by year; due to the simplicity in deployment, operation, low cost, and user mobility offered by the technology. Wi-Fi is one of the most popular technologies that has been standardised by the IEEE committee as 802.11b WLANs. Since the first WLAN standard launched in 1997, the IEEE 802.11 technology has already been implemented to provide various network services, for example, home and personal applications, internet hotspot service and bridge for different wired or wireless networks. With increasing application of WLAN (e.g. voice over WLAN), capacity of WLANs is becoming an issue. In 2003, the IEEE 802.11 committee defines 802.11g standard to provide higher data rate and throughput. Currently, both of the 802.11b and 802.11g are widely adopted by home and office users as WLANs solution.

WLAN design is quite different from wired network design. This is because of the complex and dynamic behavior of WLANs as well as the unpredictable characteristics of radio propagation. In the wireless environment, any wireless node can hear radio signal from other wireless devices, as long as they are within the range of radio signal coverage. Radio propagation environment is one of the key factors that influences the performance of Wi-Fi networks. Signal strength becomes weaker in a harsh propagation environment compared to a good propagation environment.

With widely deployment of Wi-Fi networks, it encourages researchers devote extensive efforts to study the performance and issues in the area of WLAN. Many researches have focused on improving MAC and PHY of the IEEE 802.11 [1-3], request to send / clear to send (RTS/CTS) handshaking mechanism [4, 5], and transmission power management [6-8]. In addition, base station placement is also an important aspect in terms of WLAN performance in the indoor environment [9-11]. Base station placement is a challenging task, especially in an obstructed office environment due to dynamic characteristics of radio wave propagation.

The infrastructure mode is widely used in the WLAN deployment. An access point (AP) coordinates transmission in an infrastructure network. The location of an AP is an important factor that influences WLAN performance. A single AP may not provide adequate signal coverage in the large organization. The deployment of multiple APs is quite common in the organization. However, the placement of multiple APs is more complex than a single AP placement. A careful plan of WLAN deployment not only saves cost but also enhances network performance and efficient radio resources utilisation.

WLAN performance evaluation and analysis can be performed by: (1) propagation measurement; (2) analytical modeling; and (3) computer simulation. To get an insight into the signal strength in a crowded office environment, a radio propagation measurement is required. Propagation measurement enables us to find the relationship between Wi-Fi link throughput and signal strength. Many factors affect the received signal strength (RSS) in an indoor environment, for example, multiple-path propagation and human motion [12].

The IEEE 802.11 standard provides various WLAN architectures and topologies for WLAN design (e.g. basic service set, extended service set, ad-hoc mode, infrastructure mode). Unlike normal AP mode, advanced APs could provide various AP configuration modes. Wireless distribution system (WDS) mode is example of an advanced AP. Different operating modes of APs may have different WLAN performance as well as implementation cost. Careful consideration of WLAN configuration is needed because otherwise it would impact WLAN performance, implementation cost, and effective management of radio resources.

The objective of this dissertation is discussed next.

## 1.1 Objective of This Research Project

The aim of this research is to investigate the impact of signal strength on Wi-Fi link throughput in an obstructed office environment. We examine the relationship between signal strength and Wi-Fi link throughput through propagation measurements. Moreover, to provide a good signal coverage and throughput, we seek the optimal locations for

APs placement as well as provide an in-depth analysis of AP configurations to meet different user requirements. The study also observes the optimum number of APs for a particular office setting.

An additional contribution of this study is to propose some recommendations in terms of practical AP deployment. The WLAN capacity planning is also discussed.

The structure of this dissertation is presented next.

## 1.2 Dissertation Structure

The remainder of this report is organized as follows. In chapter 2, we report on literature review of IEEE 802.11 protocols and challenges in wireless propagation measurements. Chapter 3 describes the research methodology, with a comparison of the computer simulation and analytical modeling methodologies. Chapter 4 reports on radio propagation measurements, including hardware and software requirements and measurement setup. In chapter 5, we present summary of experimental results. The research implications and future directions are discussed in chapter 6, and chapter 7 concludes the report.

# Chapter 2

# Background and Related Works

This chapter provides a review on literature in the areas of signal strength and throughput measurement. We first provide a brief overview of the IEEE 802.11 standards. It provides an essential background of WLAN architecture. We then provide a review of IEEE 802.11 covering both MAC and PHY layers. Finally, the recent studies in WLAN throughput, base station placement, the quality of radio signal, propagation measurement and signal strength with its application are discussed.

## 2.1 Overview of the IEEE 802.11 Standard

The IEEE 802.11 standard was published in October, 1997. The standard covers both MAC protocol and physical layer. The initial standard only supports low data rates (1 and 2 Mbps) and operates at 2.4GHz ISM band. The standard employs frequency-hopping spread spectrum (FHSS) and direct-sequence spread spectrum (DSSS) techniques for radio transmission [13].

The IEEE 802.11a and 802.11b amendments were approved by IEEE 802.11 committee in October 1999. The IEEE 802.11a standard is also known as *"high-speed physical layer in the 5 GHz band"* [14]. The IEEE 802.11a operates at 5 GHz unlicensed band and supports up to 54 Mbps by using orthogonal frequency division multiplexing (OFDM). Due to heavy loading of ISM band, the IEEE 802.11a standard has an advantage of less interference. However, the high carrier frequency (5 GHz) results in limited transmitted range than 2.4 GHz [15].

In contrast, the IEEE 802.11b *(Higher-Speed physical layer extension in the 2.4 GHz)* was published later than the IEEE 802.11a. However, the IEEE 802.11b product was launched earlier than the IEEE 802.11a product and has much larger radio coverage than the IEEE 802.11a product. The IEEE 802.11b adopts high rate direct sequence spread spectrum (HR/DSSS) technique and complementary code keying (CCK) modulation scheme to provide higher data rates (5.5 and 11 Mbps). Since the IEEE 802.11b operates in the 2.4 GHz ISM band, it also adopts DSSS technique to support low data rates (1 and 2 Mbps).

With comprehensive application of WLAN, higher data rate and throughput is required by multimedia application. The IEEE 802.11g standard, as known as *"further higher data rate extension in the 2.4 GHz"*, was published in June 2003. By comparison with the IEEE 802.11b, data rate and throughput of the IEEE 802.11g has significant improvement (up to 54Mbps) and radio coverage is larger than the IEEE 802.11b. Moreover, one of the advantages of the IEEE 802.11g is that it is backward compatible with the IEEE 802.11b. Therefore, the IEEE 802.11g and 802.11b have become mainstream standards of WLAN products nowadays.

The IEEE 802.11 networks have two operation modes: (1) Ad-Hoc; and (2) Infrastructure [16]. An infrastructure network involves an AP as a coordinator between wireless stations (as shown in figure 2.1). On the other hand, an ad-hoc network is formed by two or more wireless stations without AP involved (as shown in figure 2.2).

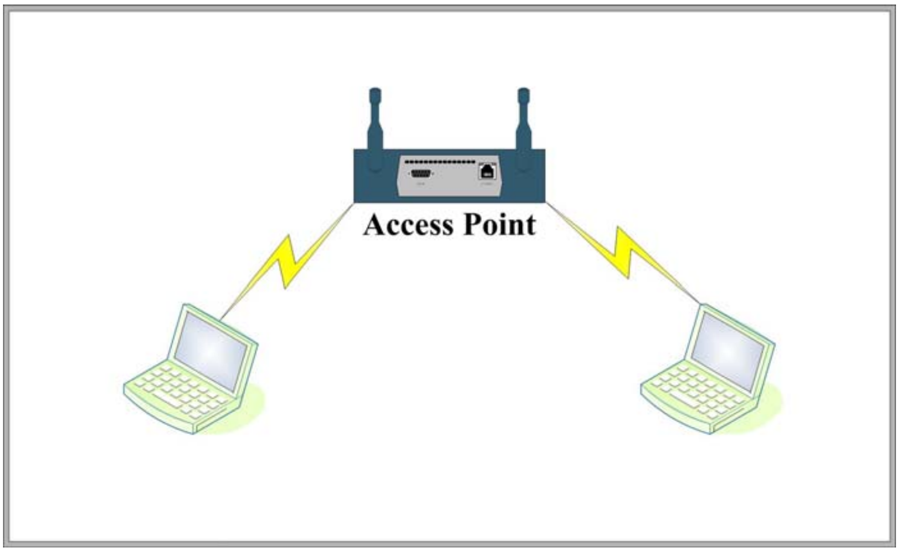


Figure 2.1: An infrastructure network.

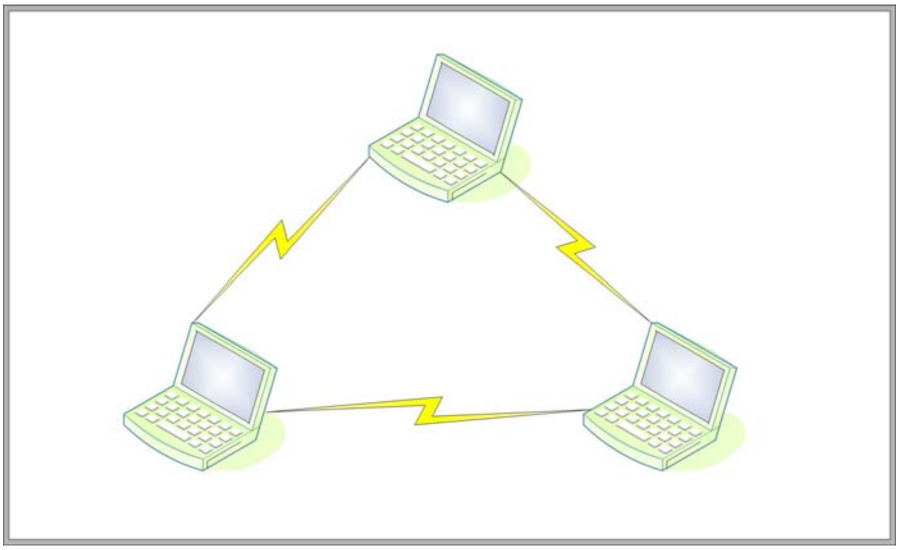

Figure 2.2: An ad-hoc network.

The IEEE 802.11 networks have three different network architectures: (1) basic service set (BSS); (2) independent BSS (IBSS); and (3) extended service set (ESS) [13]. BSS is a basic architecture of the IEEE 802.11 network. It may include two or more wireless nodes. The nodes can be a wireless workstation or an AP. All wireless nodes share a signal coordination function in the same BSS. Figure 2.3 shows three BSSs and each BSS has an AP and two wireless stations. IBSS is the smallest service unit in the IEEE 802.11 network (as shown in figure 2.4). The advantage of the IBSS is that it can enable two wireless stations to form a WLAN without an AP.

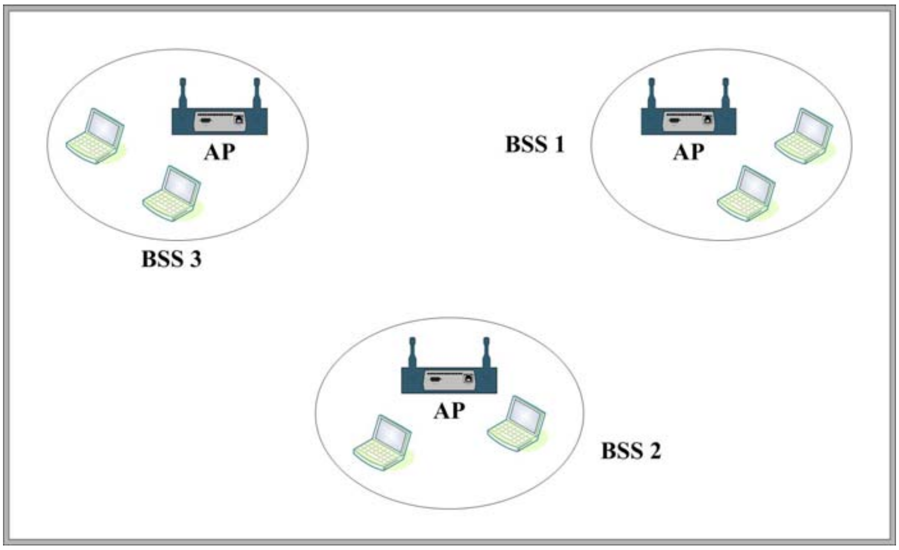


Figure 2.3: Basic service set.

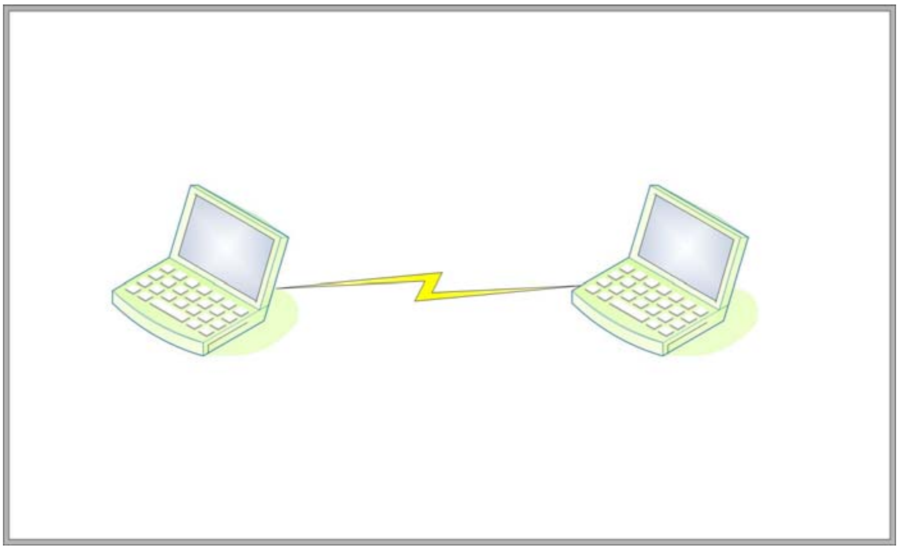

Figure 2.4: Independent basic service set.

The coverage of a BSS is limited due to limited transmission power. Some organizations may require two or more BSSs to cover entire organization. In order to provide service between different BSSs, it requires a distribution system (DS) which is a logical unit between different BSSs [13]. The main function of a DS is to provide interconnection and seamless services among the multiple BSSs. The DS can be wired connection or wireless connection. With wireless DS, the role of an AP is not only a coordinator between wireless stations within BSS, but also provide links to other BSSs. Figure 2.5 shows an ESS which is comprised of three BSSs and a wireless DS (WDS).

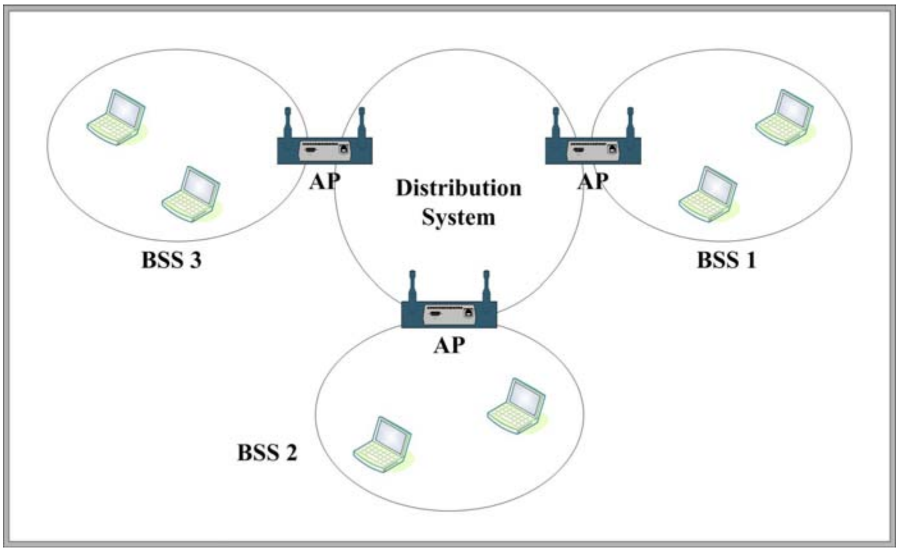


Figure 2.5: ESS and wireless distribution system.

Figure 2.6 shows an ESS architecture with a wired DS. The DS and BSSs provide flexibility to create various sizes of WLANs. The ESS is comprised of multiple DSs and BSSs [17]. All wireless stations and APs share the same logical link control (LLC) layer within the same ESS.

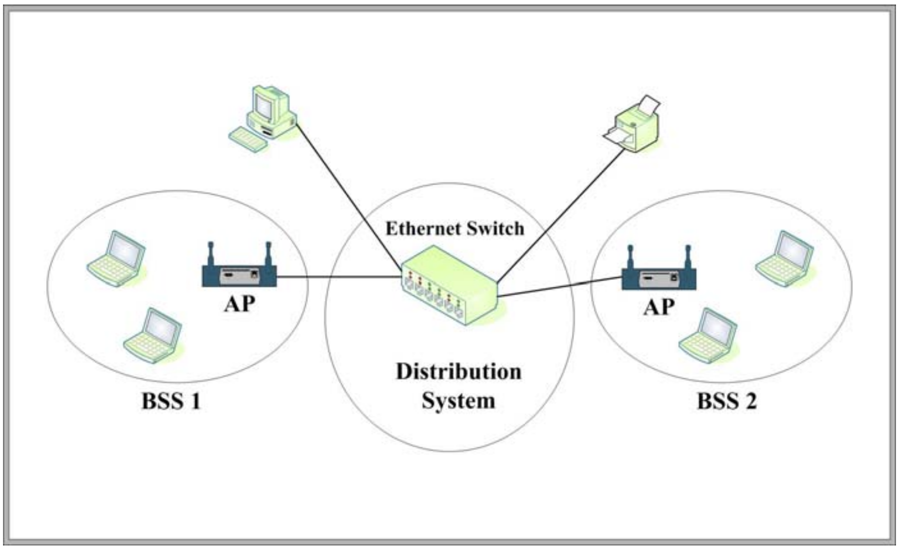


Figure 2.6: ESS and wired distribution system.

## 2.2 The IEEE 802.11 Protocols

Figure 2.7 shows protocol architecture of the IEEE 802 family. As Ethernet and Token-Ring, the IEEE 802.11 standard defines both the physical and MAC layers. Although the IEEE 802.11a, 802.11b and 802.11g adopt different physical layer technologies, they share a common MAC, LLC and use same link layer address space (48-bit).

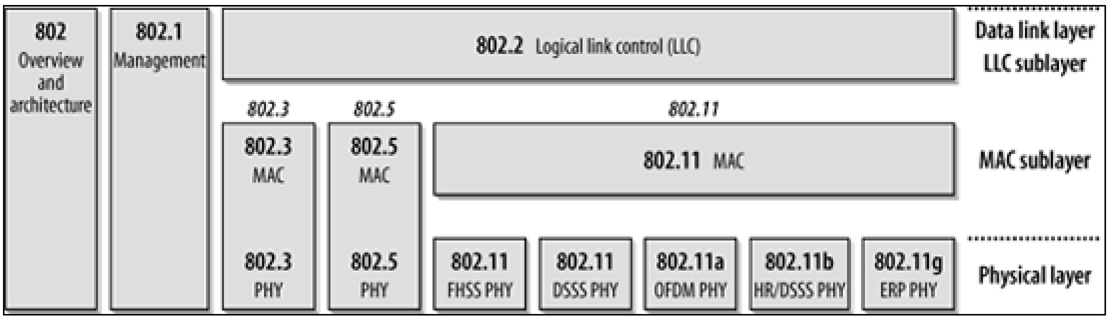


Figure 2.7: The IEEE 802 family and OSI model [14].

### 2.2.1 Physical Layer

Figure 2.8 shows the physical layer architecture of the IEEE 802.11 standard. The IEEE 802.11 PHY is comprised of two sub-layers: (1) physical layer convergence procedure (PLCP); and (2) physical medium dependent (PMD) [14]. The PLCP is responsible for converting MAC frames into transmitting frames. The PMD function defines the transmitting method over wireless medium between wireless nodes.

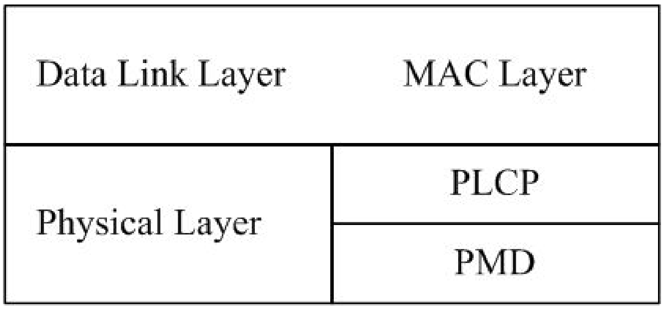


Figure 2.8: Physical layer logical architecture.

In order to support various data rates, the IEEE 802.11 standards define several spread spectrum and modulation techniques. Spread spectrum is a crucial technology that is used for data transmission at the ISM band. Traditional telecommunication technology concentrates upon putting much signal into a narrow band. However, spread spectrum uses mathematical methods to distribute signal power over a large band. Due to less potential interference, spread spectrum technique is an important requirement for radio devices to operate at the ISM band. In the USA, the Federal Communication Commission (FCC) requires that radio equipment which operates at the ISM band has to use spread spectrum technology [18].

Nevertheless, spread spectrum technology cannot resolve interference problem completely. Due to minimizing interference at the ISM band, the FCC has the power regulations to control transmitting power of wireless devices at the ISM band. The legal output power is one Watt (1w) and the effective radiated power is four Watts (4w) [18]. Three spread spectrum technologies: FHSS, DSSS and OFDM are adopted in the IEEE 802.11 standards. The original IEEE 802.11 standard supports three physical layers: FHSS, DSSS and infrared (IR) [13]. IR PHY and FHSS PHY support 1 Mbps with an optional 2 Mbps. DSSS PHY supports both 1 Mbps and 2 Mbps.

The IEEE 802.11a standard uses OFDM technique to support higher data rate. OFDM technique divides a channel into 52 sub-carriers, including 4 pilot carriers and 48 data carriers and then distributes signals into 52 sub-carriers [14]. In order to support various data rates, OFDM uses different modulated techniques (refer table 2.1)[19]. For example: 64-QAM modulation is used for 54 and 48 Mbps data rate.

| **Data rate (Mbps)** | **Modulation Technique** |
| --- | --- |
| 6 | BPSK |
| 9 | BPSK |
| 12 | QPSK |
| 18 | QPSK |
| 24 | 16-QAM |
| 36 | 16-QAM |
| 48 | 64-QAM |
| 54 | 64-QAM |

Table 2.1: Data rate and modulation techniques for the IEEE 802.11a.

The IEEE 802.11b offers higher data rates (5.5 and 11 Mbps) in addition to 1 Mbps and 2 Mbps by using 8-chip CCK. The IEEE 802.11b standard has some optional features to improve data throughput, for example, packet binary convolutional coding (PBCC) is an alternative coding method. The PBCC provides higher data rate (22 Mbps) than CCK modulation. Another optional feature is a short preamble mode, such as HR/DSSS/short and HR/DSSS/PBCC/short. With enabled short preamble function can improve throughput significantly at higher data rate [20]. Operating frequency of the IEEE 802.11b and 802.11g are from 2.4 GHz to 2.4835 GHz.

The IEEE 802.11g standard contains three compulsory components: Extended Rate PHY (ERP)-DSSS, ERP-CCK and ERP-OFDM, and two optional components: ERP-PBCC and DSSS-OFDM [21]. The ERP-DSSS module and ERP-CCK module are backward compatible with the IEEE 802.11b standard. The ERP-OFDM is a core component of the IEEE 802.11g. As the IEEE 802.11a, OFDM is used by the IEEE 802.11g as spread spectrum technique to provide high speed data rate. Furthermore, ERP-PBCC is an optional feature in the IEEE 802.11g standard to provide 22 Mbps and 33 Mbps data rate. DSSS-OFDM is an optional feature as well. DSSS-OFDM uses DSSS as header for encoding packet and the OFDM for encoding payload [21]. The reason to define the DSSS-OFDM feature is for backward compatible with the IEEE 802.11b standard. In addition, due to backward compatible with the IEEE 802.11b, the IEEE 802.11g uses CCK as modulated technique for 5.5 and 11 Mbps and DSSS for 1 and 2 Mbps.

### 2.2.2 Medium Access Control

The IEEE 802.11 employs carrier sense multiple access and collision avoidance (CSMA/CA) for medium access control. Both Ethernet and the IEEE 802.11 stations use carrier-sense mechanism to gain privilege to access media. The IEEE 802.11 MAC layer includes two sub-layers: (1) distributed coordination function (DCF); and (2) point coordination function (PCF) (as shown in figure 2.9) [13].

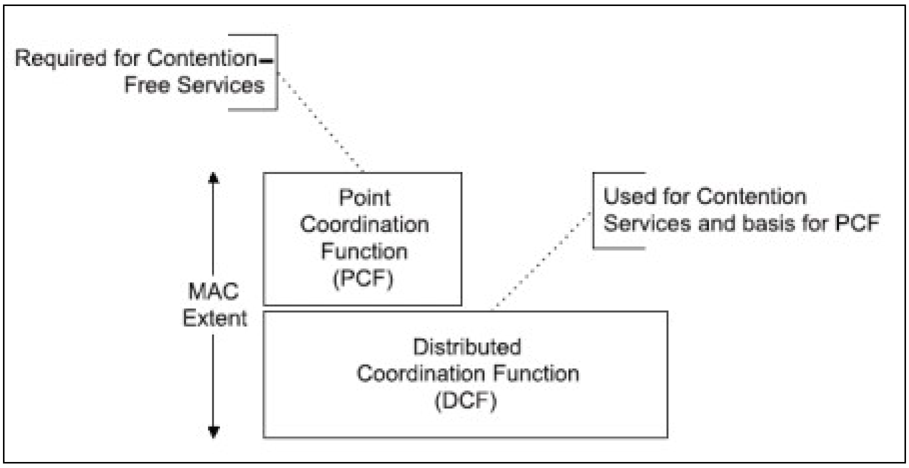


Figure 2.9: IEEE 802.11 MAC architecture [13].

DCF is a default medium access control mechanism of the IEEE 802.11, as known as CSMA/CA. DCF is implemented within wireless stations and APs. Thus, DCF supports both Ad-hoc mode and infrastructure mode. Furthermore, in order to reduce collision, a random back-off time is used to resolve conflict during media contention.

On the other hand, PCF is an optional feature which incorporates with DCF to provide a contention-free service. PCF requires point coordinators to ensure that the medium can provide a contention-free service. Point coordinators only exist in the AP, so PCF is available in the infrastructure mode.

When PCF is enabled, time on medium is separated into two periods: contention-free period (CFP) and contention period. CFP is controlled by PCF and contention period is handled by DCF. An AP delivers a "*beacon frame*" at the beginning of CFP. In order to prevent DCF-based service to access medium, "*beacon frame*" is to lock out wireless medium by setting the maximum duration of CFP in all wireless stations.

DCF is designed to provide "best-effort" service. Although PCF is designed to support real-time service, hidden nodes problem would lead to collisions during a contention-free period [22]. PCF is not an ideal protocol to support quality of service (QoS) and real-time application. The IEEE 802.11 committee proposed a new standard, called 802.11e, to support QoS and fair service in the IEEE 802.11 MAC layer. The IEEE 802.11e is a dominant protocol than PCF in QoS and fair service.

## Carrier-Sense Mechanism

The IEEE 802.11 defines two types of carrier-sense mechanism: physical carrier-sense and virtual carrier-sense [13]. Physical carrier-sense is provided by PHY. Virtual carrier-sense mechanism is handled by MAC. Either one of carrier-sense indicates that the medium is busy. The medium should be busy, otherwise, it can be considered as idle. The virtual carrier-sense uses network allocation vector (NAV) to reserve the medium for a fixed time period. The function of the NAV is a timer to indicate the amount of time that the medium will be reserved. The carrier-sense mechanism uses NAV state, transmitter status and physical carrier-sense to determine the status of the medium.

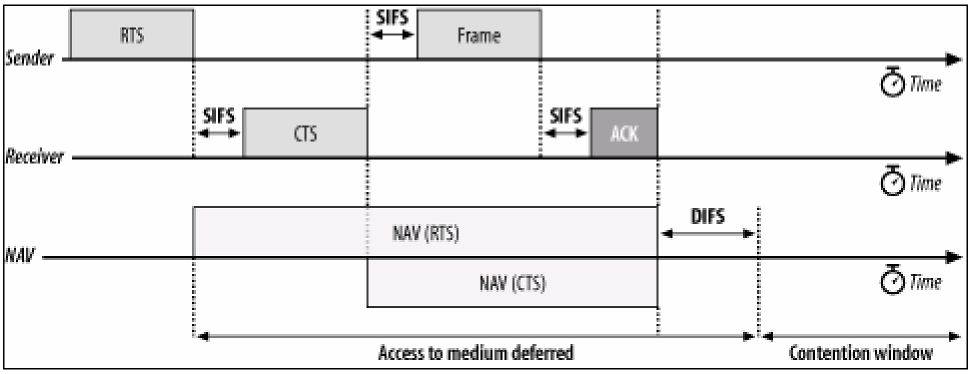


Figure 2.10: Network allocation vector [14].

The function of the NAV is shown in figure 2.10. A sender and a receiver reserve the medium by using NAV. The sender and receiver set up the NAV. Other stations count down from the NAV to 0. If the NAV is not 0, it indicates the medium is busy. On the other hand, when the NAV is 0, the medium is available. The advantage of the NAV is to prevent interruption from other wireless stations during a sequence of frame transmission [14].

### Random Backoff Time

Before data transmission starts, a wireless station uses carrier-sense mechanism to determine if the medium is busy or idle. If the medium is busy, the wireless station will put back a DCF interframe space (DIFS) or an extended interframe space (EIFS). After DIFS and EIFS, the station will generate a random backoff time for another deferral before transmission. The main purpose of the random backoff time is to reduce probability of collision during the period of contention between wireless stations. The formula which is used to generate random backoff time is given below,

$$Backoff\ Time = Random\ () * a\ SlotTime \text{ [13]}$$

Random () is a pseudorandom integer which is determined by the contention window parameters. The value of aSlotTime is determined by characteristics of physical layer.

Figure 2.11 shows the backoff procedure. As mentioned in [13], in the beginning of backoff procedure, the wireless station set backoff timer by using the backoff time formula. If the medium is free, the backoff procedure will deduct the aSlotTime time from backoff timer. If the medium is busy during a backoff time slot, the backoff procedure will be suspended. Then the medium will be determined busy or idle during DIFS or EIFS period before backoff procedure resumes. However, when the backoff timer reaches 0, transmission will start immediately.

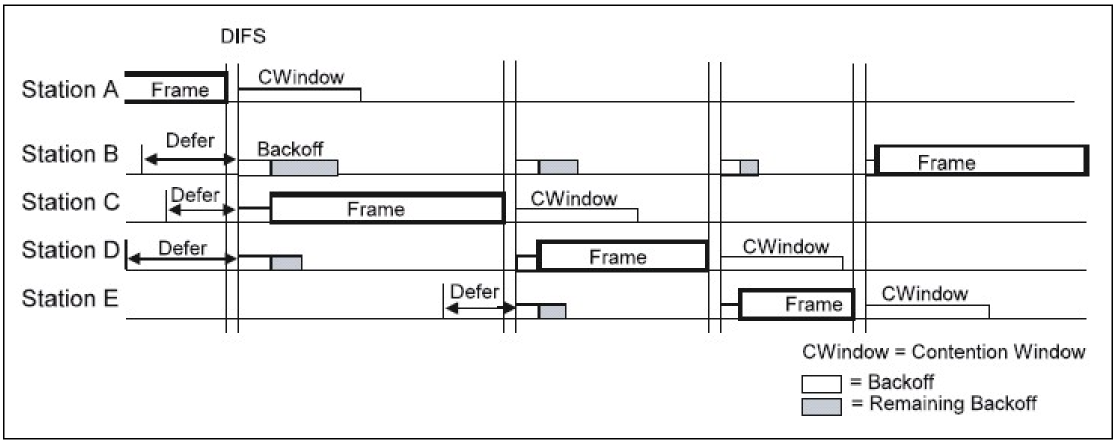


Figure 2.11: Backoff procedure [13].

### 2.2.3 Radio Propagation Characteristics

Although radio wave propagation is a complicated topic, it is necessary to understand the characteristics of radio propagation in WLAN design. In fact, radio wave propagation is influenced by many factors for instance, distance, radio frequency, geographical features, transmission power and reflections [18]. Therefore, it is very difficult to accurately estimate signal strength and quality of signal by analytical modeling and simulation in a particular propagation environment. Both the signal strength and radio propagation are affected by several factors, such as interference, multiple-path propagation, path loss and attenuation.

#### Interference

Man-made noise is a serious issue at 2.4 GHz ISM band. Many industrial, medical equipment and household appliances, for example, microwave ovens, Bluetooth devices, are operating at 2.4 GHz ISM band. When too many ISM devices operate in a small area, it results in interference as well as decline in performance. Especially, interference not only causes higher frame error rate, but also higher re-transmission rate.

The interference from microwave oven is a quite common problem to degrade the performance of WLAN. Many previous studies have already addressed that microwave ovens have strong influence on the performance of WLANs [23-26].

Similar to WLAN devices, Bluetooth equipment shares 2.4 GHz ISM band as well. Bluetooth technology is widely used for data transmission between personal devices, for example laptop, PDA, mobile phone, and print. However, while Bluetooth devices and WLAN are operating concurrently and very closely, it could cause coexistence interference and degrade the performance of both devices [27-31]. Furthermore, as mentioned in [32], if the distance between Bluetooth devices and WLAN devices is less than 2 meters, the throughput will degrade significantly. Due to the interference from Bluetooth devices, throughput of the IEEE 802.11b stations degraded from 25% to 66% [33]. Furthermore, when Bluetooth interference leads to packet loss of WLAN, it cannot be solved by increasing transmission power of WLANs. However, decreasing transmission power of WLANs can mitigate the effects of interference to Bluetooth devices [31].

Even though the IEEE 802.11 standard defined 14 channels, only 3 non-overlapping channels (channel 1, 6 and 11) are available [34]. While two of APs are using same channel or adjacent channels, it could cause co-channel interference. The throughput would degrade 2 Mbps in the IEEE 802.11b WLANs due to adjacent channel interference[35]. Thus, co-channel interference results in reducing the capacity of WLAN, inefficiency of using radio spectrum and increasing deployment cost [18, 36].

In order to mitigate effects of co-channel interference, different orthogonal code sets CCK (DOC-CCK) modulation was developed instead of the IEEE 802.11b CCK modulation in [37]. According to simulation results, the DOC-CCK almost eliminates co-channel interference when two BSSs are located in the same area.

In conclusion, interference of radio frequency is a usual problem and has significant impacts on data throughput in wireless communication. The studies give us an insight into understanding the impact of interference on WLAN performance and mitigating the effects of interference. The studies also have profound implications for propagation measurement.

## Multiple-Path Propagation

Reflection or diffraction leads to multiple-path propagation. Multiple-path propagation is a common event in the indoor environment. The radio signal would reflect from objects during transmission (e.g. wall, ceiling and office partition). The effect of multiple-path propagation causes the fading of radio signal, so that receiver would not get sufficient signal power [36]. Moreover, the reflected signals will arrive later than direct signal. The period used to identify duplicate signals is referred to *"delay spread"*. In general, the large delay spread number has better performance, because stations and APs have enough time to identify radio signals [38].

## Attenuation

When data transmission occurs between two wireless nodes, the signal power is dropping and getting weak. It is called attenuation [36]. Many factors could result in attenuation, for example, distance, obstruction, and multiple-path effect. Due to attenuation, received devices would not have sufficient signal strength. The performance would degrade significantly. Furthermore, metal door and structural concrete wall have a greater impact on signal attenuation than other constructional materials in the indoor environment (refer table 2.2).

| **Materials** | **Attenuation** |
|---|---|
| Plasterboard | 3 to 5 db |
| Glass wall with metal frame | 6 db |
| Cinderblock wall | 4 to 6 db |
| Window | 3 db |
| Metal door | 6 to 10 db |
| Structural concrete wall | 6 to 15 db |

Table 2.2: Signal attenuation with different constructional material [18].

## 2.3 WLAN Signal Strength Measurement

This section reviews recent articles of WLAN performance, base station placement, signal quality impacts, WLAN measurements, signal strength and its application.

### 2.3.1 WLAN Performance

Figure 2.12 shows effective throughput with different kinds of network overheads. The overhead of the IEEE 802.11 is quite high, so that it has a large gap between practical throughput and data rate. As mentioned in [39], the overhead of the WLAN is around 60%. Only 40% time is used to transmit payload. The reset of time is consumed by re-transmission (35%), acknowledgement (15%) and management traffic (10%). Thus, to obtain an accurate saturation throughput of WLAN from experimental measurements, test environment control and minimizing possible interfering factors would be helpful to gain better and realistic saturation throughput. For example, shutdown unnecessary services (e.g. disable simple network management protocol (SNMP) function).

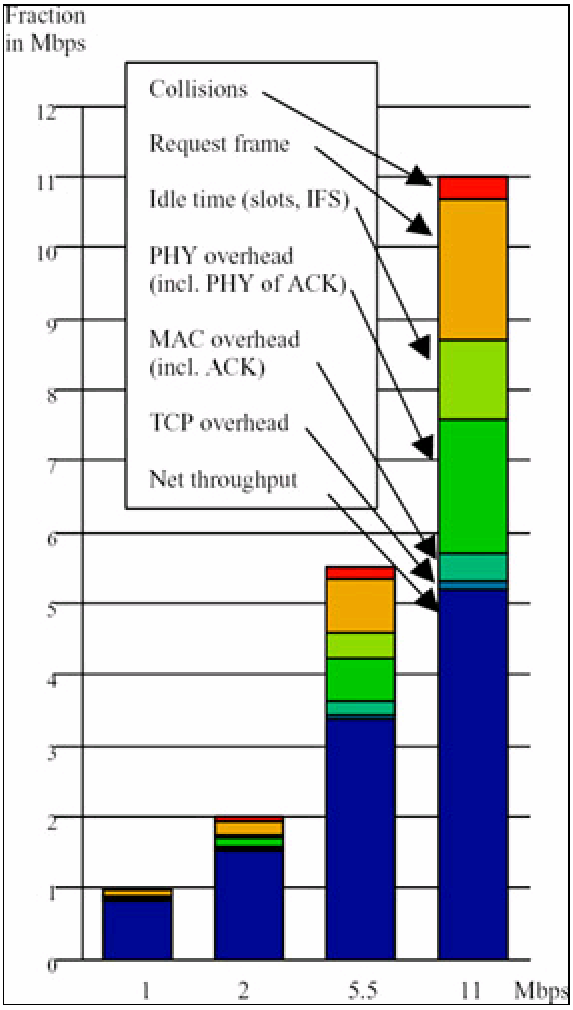


Figure 2.12: Net throughput of IEEE 802.11b [17].

The overhead of “request to send/clear to send” (RTS/CTS) was addressed in [40, 41]. Figure 2.13 shows effective throughput and various overheads including RTS/CTS. Although RTS/CTS would result in additional traffic, existing literature also indicated that the RTS/CTS can reduce the hidden nodes problem and improve the throughput in multiple stations environment [40, 42-44].

However, RTS/CTS handshake mechanism is not as good as expected [4, 5]. The functionality of RTS/CTS does not work properly when the distance between a receiver and a transmitter is larger than 0.56 times of transmission range. The IEEE 802.11

RTS/CTS cannot resolve hidden nodes problem completely. A new MAC layer schema: the conservative CTS reply (CCR) can be used to solve the above problem [5].

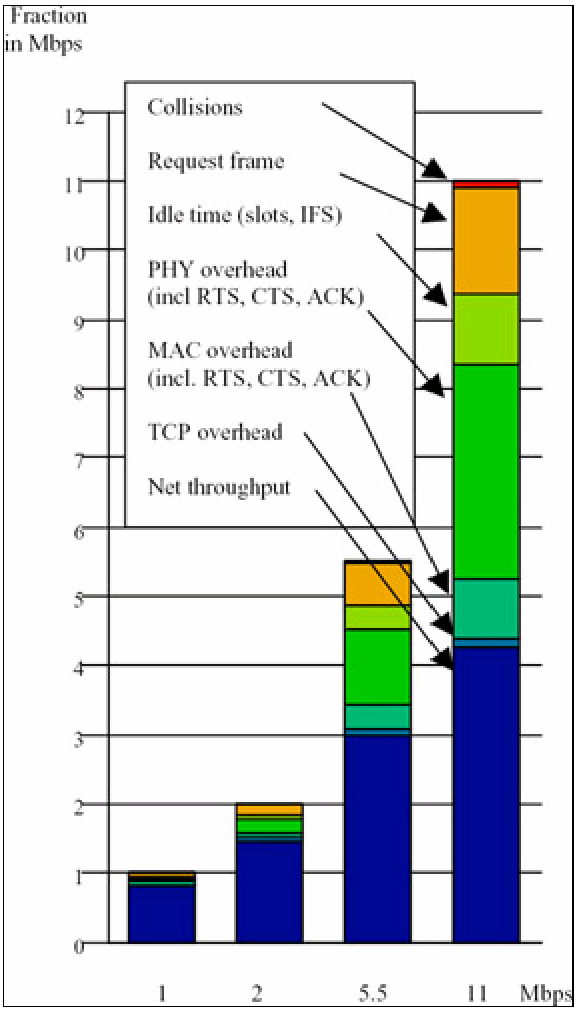


Figure 2.13: Net throughput with 802.11b including RTS/CTS [17].

An experimental measurement was conducted to investigate effective TCP throughput and used analytical modeling to find MAC throughput in [45]. The experimental study indicated that the MAC throughput is around 15% to 20% higher than effective TCP throughput. The results showed that effective throughput is increased from 47% to 82% when data rate shifts from 11 Mbps to 1 Mbps.

As highlighted in [46, 47], distance, buffer size and fragmentation have important effects on WLAN throughput. With increasing distance, signal power is attenuated gradually and packet loss rate is increased. The data buffer also plays a significant role in WLAN. The function of data buffer is used to keep packets which are from high layer protocols (e.g. network, TCP layer). Packets will be dropped when the buffer is full, thus, smaller buffer size would result in the lower throughput. Appropriate buffer size is between 64000-128000 bits in the IEEE 802.11b networks [10]. Small fragmentation (packet size) would have better throughput in higher radio interference environment. However, large fragmentation would provide higher throughput in a good radio propagation environment.

As mentioned in [48], the low height of antenna and short distance between a receiver and a transmitter would cause significant path loss. The radio propagation of WLANs would be limited within quite short ranges because of the Fresnel zone (as shown in figure 2.14).

Anastasi et al. [49] pointed out that only when the height of both laptops is 1 meter from the ground and the distance between two laptops is more than 33 meters, the Fresnel Zone will touch the ground (refer figure 2.14). If the height of both laptops is either 1.5 or 2 meters, the Fresnel zone will only touch the ground when the distance between laptops is greater than 73 meters and 131 meters. The communication range would increase if the Fresnel zone is kept at a level away from the ground. In addition, when any object (for example, table, chair and the ground) is located in the Fresnel zone, it results in diffraction and degrades the signal power. Therefore, the height of antenna has a significant impact on throughput in the IEEE 802.11b network. The throughput increases by 100% when the height of wireless devices changes from 0.4 to 0.8 meter.

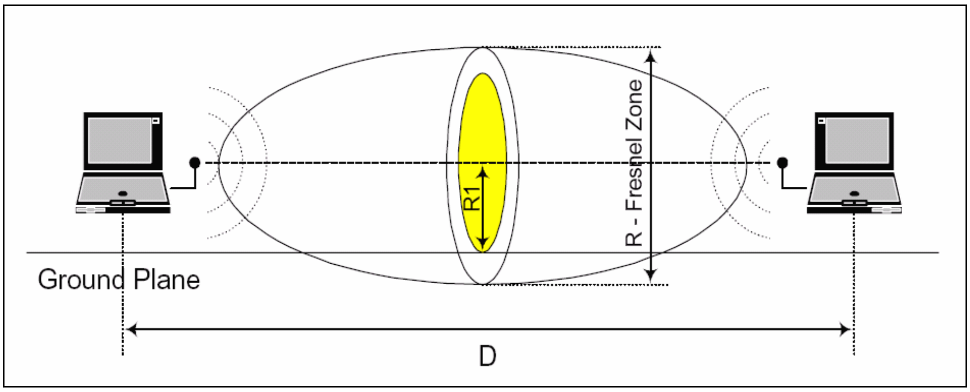


Figure 2.14: The Fresnel Zone [49].

The impact of power management on WLAN throughput was addressed in [17]. Power management is an efficient way to extend battery life. However, it results in low throughput of WLAN due to lower transmission power. Enabling power management function will decrease performance of WLAN around 240%. The study gives us an insight into power management control during propagation measurement.

The highest data rate would have maximum network throughput. RSS and frame error rate are key factors to determine the exact data rate [50, 51]. Poor signal strength not only leads to lower throughput, but also small range of signal coverage. RSS is an important benchmark for assessing the performance of WLANs.

To sum up, the studies give us an insight into experimental measurement design and considering interfering factors. The studies also have an important implication of conducting further experiment in the obstructed office environment.

### 2.3.2 Base Station Placement

An accurate base station placement can reduce the number of base stations, adequate signal coverage of desired area, spectral efficiency and lower installation costs. Many studies have already indicated that base station placement has strong influence on network throughput, channel assignment, and efficient spectrum utilization in the indoor and outdoor wireless network [52-56]. Maximizing system capacity, utilizing spectrum more efficiently and improving quality of service are primary goals of WLAN design. An effective base station placement plan is necessary prior to practical deployment. The measurement of signal strength is an approach to estimate coverage of APs. Signal strength meter is widely used to measure signal strength of WLAN. Some computer software (e.g. Wirelessmon [57]) would also provide same functionality of signal strength meter. Signal strength map is a common technique to present WLAN performance in the practical WLAN design.

Non-parametric modeling technique was developed for estimating signal strength and conducted measurements to validate a proposed model [58]. The study has a significant implication of using realistic signal strength for optimizing AP placement.

There are only three non-overlapping channels in the IEEE 802.11 networks. Utilising spectrum as efficiently as possible is important in the base station placement. Due to overlapping channels, it results in co-channel interference. The effect of co-channel interference has already been discussed in chapter 2.2.3. Therefore, base station placement not only concentrates on signal coverage, but also selecting frequency and channel assignment [59, 60].

The essential requirements of base station placement include adequate signal coverage, good signal quality and less interference. In order to optimize radio signal coverage, it is necessary to observe the radio propagation environment. In general, a wireless base station could cover quite large area in the free space. However, the behavior of radio propagation becomes complicated and dynamic in indoor environment. Various factors related to AP placement in indoor environment were addressed in [61]. They are:

- Building or floor layout: length, width and height of room.
- Constructional materials of buildings or floors: some material is easier to cause signal reflection, multiple-path propagation and interference (e.g. concrete, mirror, glass and metal furniture).
- Specifications of AP: transmission power, antenna gain, radio frequency band, channel plan.

Computer simulation is another approach to study base station placement, WLAN performance, signal strength and radio propagation. Branch-and-bound (B&B) method was used in [54] to investigate appropriate locations for AP placement. B&B method and genetic algorithm (GA) was also adopted to seek optimal base station configuration in [9]. The result of B&B and GA comparison indicated that they are better utilised for smaller problems. B&B method is far superior to the GA method in large problem size, but the B&B method requires longer time to generate a solution.

Propagation measurement is a practical approach to understand signal strength and coverage for base station placement. Propagation measurement was used to investigate the optimal location for AP placement [62]. The study provides two important implications of candidate location selection and signal strength measurement. We also gained an insight that this would minimize the gap from different vendors or models by using the same WLAN devices for measurement and deployment.

In conclusion, the studies provide a significant insight into AP placement in indoor environment. Computer simulation may reduce time and cost in the large deployment environment. However, propagation measurement would obtain realistic results in the particular environment with little gap between experiment and deployment.

### 2.3.3 Impact of Signal Quality on WLAN Performance

The values of signal-to-noise ratio (SNR), signal-to-interference ratio (SIR) and bit error ratio (BER) have a strong impact on throughput and quality of service. Either low SNR or low SIR leads to higher BER, data re-transmission and shift to lower data rate. WLAN collision is determined by the ratio of signal-to-interference and noise (SINR). This section reviews recent studies addressing SNR, SIR, SINR and BER.

SNR is a parameter to measure the relationship between signal power and background noise. It usually measured in decibel (db). Higher SNR means less background noise implying a better WLAN performance. An exponential relationship between the SNR and network delay was addressed in [63]. The study proposed an empirical delay-SNR model that can be used for AP placement and optimal network delay.

SNR is one of the key factors for data communication in WLANs. Good SNR may lead to lower BER and would have better WLAN performance [64]. The study also showed that packet size has vast impacts on TCP throughput in WLAN; especially using small packet size could improve the throughput in the lower SNR environment. Furthermore, SNR was used to determine delivery probability and packet loss rates in [65]. The study indicated that link distance and SNR had a significant effect on packet loss rate.

SIR is a parameter to measure the signal strength and interference in the communication channel. Higher SIR means lower interference in the radio propagation environment. Higher SIR could also have large signal coverage of APs in the IEEE 802.11g environment [66]. The study proved that using *"symbol erasures"* would improve the coverage of an AP from 40% to 300% when Bluetooth device is operating close to wireless station within 1 meter to 10 meters. In addition, the *"interference avoidance procedure"* was developed to minimize the interference and increase SIR by optimizing output waveform [67].

SIR is also a benchmarking parameter for WLAN design. SIR performance has significant impacts on signal quality [68]. Signal coverage and transmission power of mobile nodes are insufficient during base station placement. It also requires a consideration of SIR performance. Inadequate SIR performance leads to path loss between base station and mobile nodes.

BER is a ratio to measure the number of error bits received to the number of total bits sent within a fixed time interval. The IEEE 802.11 DCF protocol is strongly influenced by BER. Increasing BER would result in poor throughput, longer delay and higher packet drop probability [69].

BER can be used for optimizing packet size to reduce packet drop probability and delay. A scheme called *Error Recover Service Medium-Access Control* (ERSMAC) was proposed to improve WLAN performance specially in higher BER condition [70].

Both BER and the number of re-transmitting frames are key factors to influence WLAN performance. Noise and interference have a significant impact on throughput and coverage of AP. To achieve higher data rate and throughput, it requires lower BER and higher SNIR threshold. Understanding SNR, SIR, SNIR and BER would be helpful in WLAN design. The studies have significant implications for assessing and enhancing WLAN performance.

### 2.3.4 Recommendations for WLAN Performance Measurement

Due to the complex and dynamic characteristics of signal propagation, conducting propagation measurement in WLAN is a difficult work. Various rules to improve accuracy of measurement results was identified in [71]. They are:

- Use short distance rather than long distance to ensure the signal strength could not be a factor to influence saturation throughput.
- Scan radio channel prior to experiment to avoid interference from other wireless stations or APs.
- Use small and closed room for reducing multiple-path effect when conducting experiment in open and free space is not possible.
- Turn off the unnecessary services in the AP configuration to reduce additional overhead.
- Use appropriate packet size.
- Pre-test and find out optimal orientation of the AP.
- Use appropriate file size for measuring AP throughput.

Some important environmental factors and characteristics of WLAN equipment have significant impacts on WLAN throughput. It was mentioned in [72]. The factors are:

- Distance between transmitter and receiver.
- Specifications of AP and wireless adapter.
- Material of building and partition.
- Interference from other radio equipment.
- Location of AP and signal propagation environment.
- The number of obstructions between the transmitter and the receiver.
- Antenna type: omni-directional or directional antenna, and gain of antenna.

In conclusion, the studies proposed some guidelines for conducting propagation measurement. The guidelines would be helpful for our measurement study.

### 2.3.5 Signal Strength and Indoor Positioning System

In the IEEE 802.11 standard, there is no specific definition to present the relationship between power level and RSS. Generally, RSS can be measured by mW or dBm. RSS and packet error rate (PER) are two important metrics in the adaptation algorithm. Two new adaptations were developed in [73]. Receiving-sensitivity adaptation can be used to reduce WLAN collision. Clear-channel-assessment adaptation is used to mitigate the hidden/exposed node problems. Both adaptations were based on RSS and PER.

The IEEE 802.11 technology is widely deployed for indoor ubiquitous computing and positioning systems in recent years. Many existing literatures indicated that RSS of AP can provide sufficient information to determine location of objects [74-78]. Many indoor positioning systems are based on RSS; therefore, the accuracy and reliability of the positioning systems are influenced by RSS, radio propagation environment, specifications of AP and WLAN adapter.

As highlighted in [79], the first phase of creating RSS base positioning systems has to conduct a field measurement to build up location fingerprinting database as known as radio map. The second phase is to obtain precise location from position calculation based on the measurement data.

Orinoco WLAN cards was used in [74] to conduct a field measurement in a crowded floor for collecting RSS. The RSS results indicated that radio propagation environment and specifications of AP had significant impacts on fingerprinting database. The study has a greater implication for conducting RSS measurement.

Extensive experiments were conducted in [80, 81] to measure RF energy and RSS range in indoor environment with different WLAN cards: 3Com, D-Link, SMC, Hawking Technology, BUFFLO, PROXIM and Intel. The experimental results showed that using same WLAN cards for collecting the location fingerprint and determining the location would have consistent and accurate positioning systems. Furthermore, as mentioned in [77], specifications of computers did not affect the accuracy of positioning system, but wireless adapters had significant impact on accuracy of positioning system.

In conclusion, the studies provide rich guidelines to understand the natural characteristics of RSS and specifications of wireless equipment. The studies also offer great insights into selecting WLAN cards and APs prior to WLAN deployment and using same WLAN devices, which would also provide consistent results in RSS measurement.

# Chapter 3

# Research Methodology

A literature review in the areas of WLAN performance, signal strength and propagation measurement is represented in chapter 2. This chapter provides a discussion on research methodologies in the area of telecommunication networks.

Real experimental measurement, analytical modeling and computer simulation are well-known research methodologies for modeling and performance evaluation of telecommunication networks. Analytical modeling is based on mathematical analysis. Although analytical modeling is good for designing new network protocols and tuning network parameters, it cannot control and operate network protocols in details as well as cannot present the dynamic nature of network systems [71, 82].

Computer simulation uses computer software packages, for example, NS-2 [83], OPNET [84], to evaluate network performance or develop new network protocols. However, higher level simulation software has difficulty in obtaining detail operation characteristics of network protocols. Especially, the physical medium of WLAN is dynamic and complicated. As argued in [85], *"NS-2 does not implement the physical layer of the network stack nor does it implement the characteristics of the physical medium"* (p.23). Johnson et al. [86] pointed out that *"simulation models do not sufficiently capture radio and sensor irregularity in a complex, real-world environment, especially indoors"* (p.1). According to [64], simulation tools are insufficient for an in-depth study of WLAN in several aspects and analytical modeling has difficulty in analysis of transmission control protocol (TCP) over multiple-hops WLANs.

WLAN throughputs are subject to change due to various radio propagation environment (e.g. obstructions, constructional material) [71, 80, 81]. Therefore, it is quite difficult to understand the true characteristics of WLAN by both the analytical modeling and computer simulation.

Due to higher cost of WLAN equipments and the lack of WLAN applications, it is a challenge to perform experimental measurements in the area of WLANs. The real measurement through an experimental approach is also time consuming and labor extensive. Thus, many WLAN researches have used analytical modeling and computer simulation. However, the situation has changed in recent years. With the wide applications of WLANs and their rapid development, it encourages researchers to adopt radio propagation measurement to investigate the performance and deployment issues of WLANs. For example, Park et al. [87] investigated radio interference on WLAN throughput by using experimental measurement. Chen et al. [88] conducted public WLAN traffic and throughput measurement at four hotspots. They used measurement results to develop a throughput propagation prediction model. The model can be adopted in design, development and implementation of the IEEE 802.11 WLANs.

Nowadays, WLAN adapter is standard equipment in the mobile computers and handheld devices. The price of entry level AP is under NZ $100. The number of internet hotspots is growing rapidly. WLANs provide convenient network services for people to access internet from home, office and public place. At the same time, many WLAN performance and deployment issues are emerging. Experimental measurement is becoming an important methodology for the performance study of WLANs. Experimental measurement provides an alternative to validate the results of analytical modeling and computer simulation as well as enhances the accuracy of WLAN research.

The main challenge of indoor radio propagation measurement is to control external variables, such as signal reflection from moving objects and interference from devices operating on the same frequency [89]. Furthermore, it is difficult to make a realistic conclusion from a particular experiment [90]. An accurate WLAN performance study requires extensive propagation measurements. The propagation measurement has advantages in evaluating network performance before practical deployment or product launch. The experiment would demonstrate a representative behavior of WLAN equipment, characteristics of MAC protocols and radio propagation [71, 85].

In this dissertation, we adopted a propagation measurement approach as well as a case study approach to study the impact of signal strength on Wi-Fi link throughput in an obstructed office environment at AUT University. To collect data of signal strength and throughput, we conducted a series of experiments by using two wireless laptops and two APs. The detailed specification of measurement equipment, experimental setup and measurement scenarios are described in chapter 4.

In addition, we surveyed and reviewed recent literature in the area of IEEE 802.11 WLANs, performance measurement, base station placement, and signal strength measurements. We focused on the following databases for our literature review:

- IEEE Xplore
- ACM Digital Library
- ScienceDirect Journal database
- Google Scholar (http://scholar.google.com/)

# Chapter 4

# Experimental Design

In chapter 3, the research methodology adopted in this dissertation has been discussed. This chapter provides experimental research design, which involves the details of the hardware and software equipment, description on the propagation environment, and measurement scenarios.

In section 4.1, we describe the performance metrics, such as throughput and signal strength. Section 4.2 presents the detailed specification of hardware and software. Section 4.3 describes the propagation measurement environment and section 4.4 describes the AP and wireless adapter configuration. In section 4.5, we present experimental scenarios and section 4.6 describes some preliminary works of reducing unexpected interference prior to conducting propagation measurement. Finally, section 4.7 summarises this chapter.

## 4.1 Performance Metrics

A stopwatch is used to measure file transmission time. The link throughput of WLAN is computed by dividing the file size with the total transmission time as follows:

***Throughput (Mbps)*** *= File Size (Mbits) / Transmission Time (Seconds)*

The received signal strength is measured in “dBm”, which is an absolute unit to measure the power level in decibel (dB) of the measured power relative to one milliwatt (mW). The WirelessMon software is used to measure the received signal strength.

Although the goal of measurement focuses on Wi-Fi link throughput, it is still important to consider other network layers, including the network, transport, and application layer protocols. Colligo Workgroup software was used to provide user interface for our experiments. Microsoft Windows XP operating system provided TCP/IP protocol for network addressing and transportation control.

## 4.2 Hardware and Software Requirements

This section presents the specifications of the hardware equipment and software information which were used in this propagation measurement.

### 4.2.1 Hardware Equipment

Two laptops, two APs, two wireless adapters and two external antennas were used in this propagation measurement. The following list briefly shows specifications of laptops and WLAN equipments used in this study. The detailed specifications of WLAN equipment can be found in appendix E.

- **Laptop 1**
  - Vendor: IBM
  - Model: X31
  - CPU: INTEL Pentium M 1.7 GHz
  - Memory: 1GB
- **Laptop 2**
  - Vendor: Toshiba
  - CPU: INTEL Mobile Celeron 2.4
  - Memory: 512MB
- **IEEE 802.11b/g Access Point** [91]
  - Vendor: D-link System Inc.
  - Model: DWL-2100AP
  - Specification:

  Standard: 802.11, 802.11b, 802.11g, 802.3 and 802.3u

  Network Interface: 100 Mbps Ethernet

  Media Access Control Protocol: CSMA/CA with ACK

  Frequency Range: 2.4 GHz to 2.4835 GHz

  Wireless Distribution System:

    - AP client
    - Point-to-Point Bridge
    - Point-to Multi-Point Bridge
    - Repeater
  - External Antenna Type: Dipole with reserve SMA connector
- **IEEE 802.11 b/g USB Wireless Adapter** [92]
  - Vendor: D-link System Inc.

- Model: DWL-G132
- Specification:

Standard: 802.11b and 802.11g

IEEE 802.11 b/g Host Interface: USB

Media Access Control Protocol: CSMA/CA with ACK

Frequency Range: 2.4 GHz to 2.4835 GHz

Network Architecture Types: ad-hoc and infrastructure mode

Operating Channels: US: 11, Europe: 13, Canada: 11

Antenna: Internal Integrated Antenna

- **IEEE 802.11 b/g 2.4 GHz Antenna** [93]
    - Vendor: D-link System Inc.
    - Model: ANT24-0700
    - Specification:

Standard: IEEE 802.11b and 802.11g.

Type: Omni-Directional Indoor Antenna

Power Level of Antenna: 7dbi

Frequency Range: 2.4 GHz – 2.5 GHz

### 4.2.2 Software

- Microsoft Windows XP Professional with Service Pack 2, available at: http://www.microsoft.com/windows/products/windowsxp/default.mspx
- Colligo Workgroup Edition version 4.0.m available at: http://colligo.com/products/workgroupedition/index.asp
- WirelessMon Profession Edition version 2.0 build 1010, available at: http://www.passmark.com/products/wirelessmonitor.htm

## 4.3 Propagation Measurement Environment

The propagation measurements of this study were performed on the first floor of the WY building at AUT University. Figure 4.1 shows the layout of the floor. Theexperiment was conducted within a section of the first floor (the experimental floor area is as shown in figure 4.1 bounded by the star mark '★') . The experimental floor area is 34 meters long and 15 meters wide. The exterior walls and flooring of the entire building is made of concrete and each floor has a provision of false ceiling made up of perforated particle boards for ventilation. The entire first floor is divided into small cubicles with partitions made of particle boards and translucent glass. Each office has a metal door. Since we had no access to all the cubicles, it was possible to conduct the propagation measurements in the corridor of the first floor.

The experimental setting was placed and conducted in the meeting room as shown in figure 4.1. The meeting room is bounded by particle boards on three sides and translucent glass partition facing to corridor with glass door. The meeting room also consisted of some wooden desks and chairs.

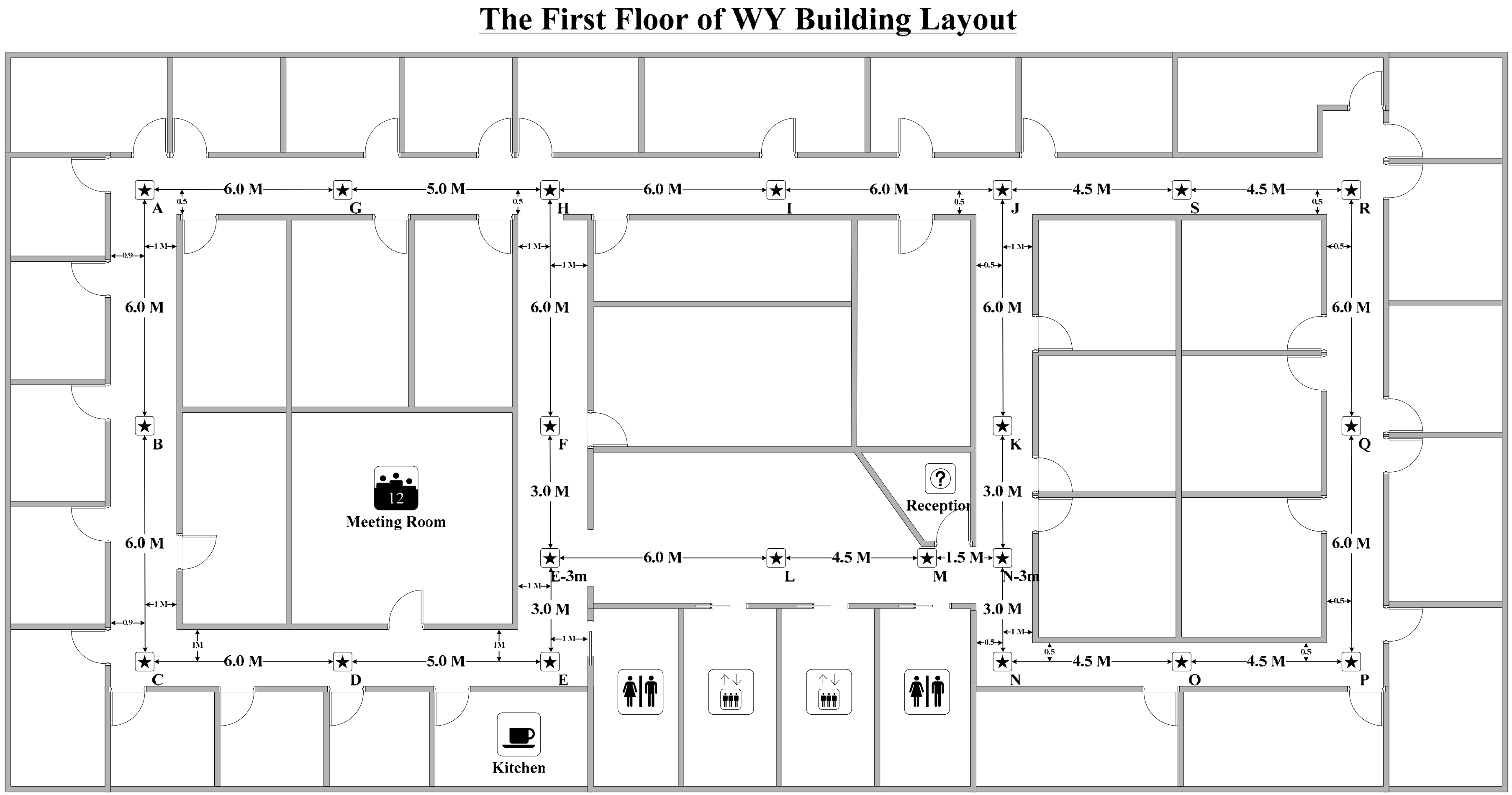


Figure 4.1: WY building layout.

## 4.4 Access Point and Wireless Adapter

This section presents AP and wireless adapter configuration including operation mode and performance parameters. We describe AP configuration in section 4.4.1. Wireless adapter configuration is presented in section 4.4.2. A brief description of AP operation mode is presented in section 4.4.3.

### 4.4.1 AP Configuration

The AP (D-Link DWL-2100AP) provides some tuning parameters due to performance and security enhancement. The setting of performance parameters of AP is described in this section. This would be useful for later researchers to conduct further research with different configurations.

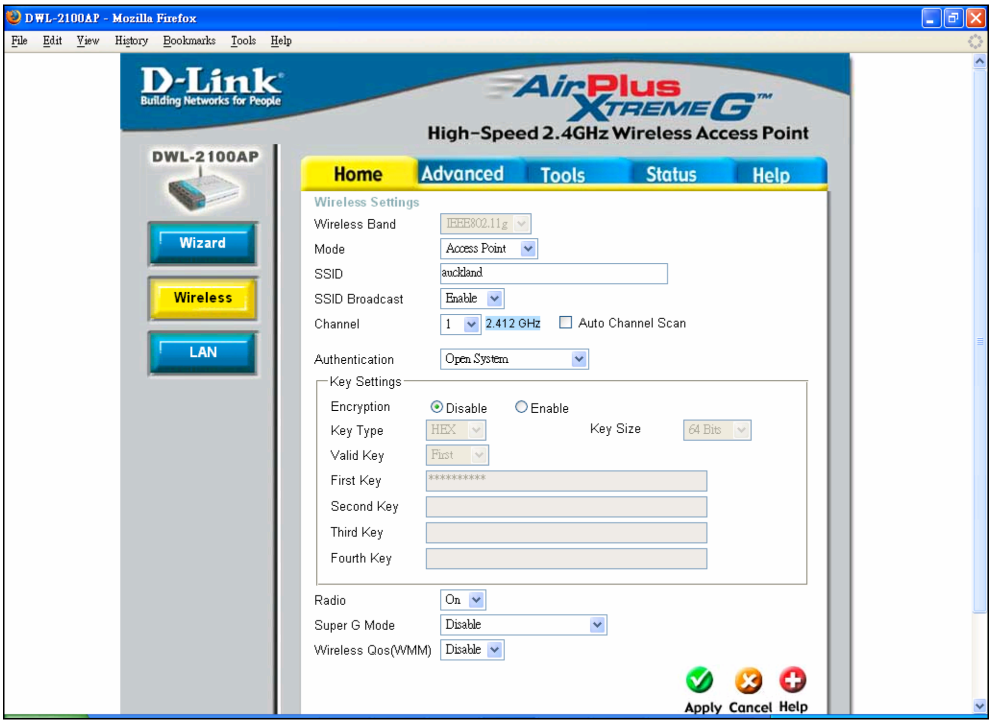


Figure 4.2: Main configuration menu for AP.

Figure 4.2 shows wireless configuration menu of the AP. This menu allows setting up SSID (Service Set Identifier), channel number, user authentication and data encryption mechanism, enable or disable functionalities of SSID broadcast, radio signal, wireless QoS and super G mode.

In a single AP scenario, we configured the AP as listed along the following settings. The channel number varied depending on available channel during measurement.

- SSID: Auckland
- Encryption: Disable
- SSID Broadcast: Enable
- Radio: On
- Channel: 1
- Super G Mode: Disable
- Authentication: Open System
- Wireless QoS (WMM): Disable

In two APs scenario, the APs used same channel number and SSID under “AP with WDS mode” and “WDS mode” configurations. On the other hand, channel number and SSID of APs should be different under “AP mode” with Ethernet configuration.

In figure 4.3, the configuration menu of performance parameter of an AP is shown. The performance parameters were set as default during the propagation measurement. RTS/CTS function is enabled by the manufacturer.

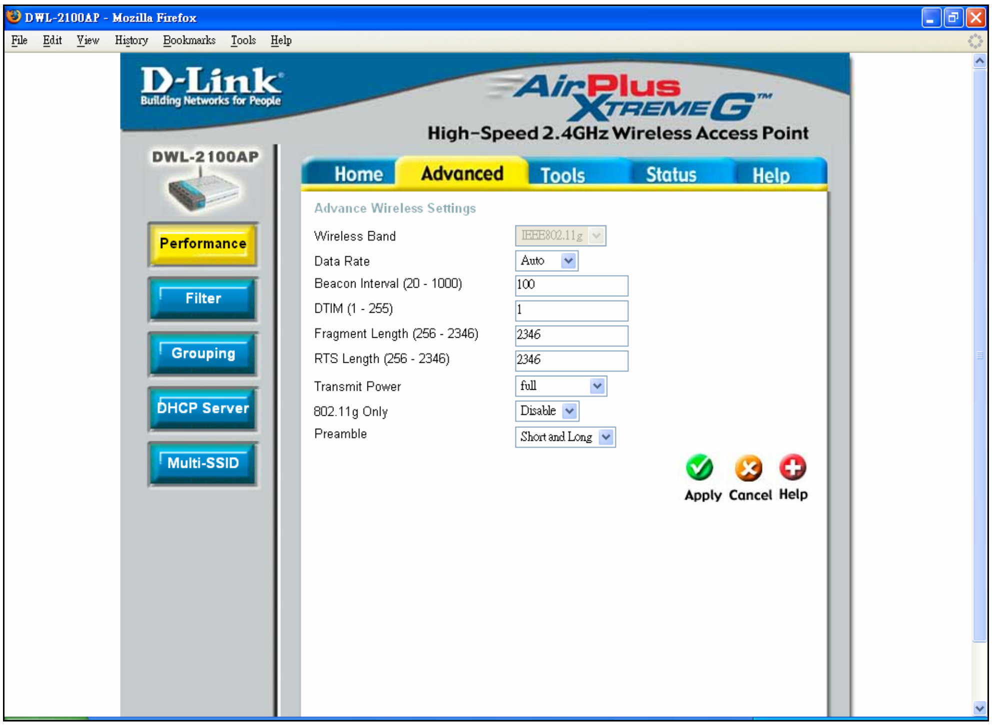


Figure 4.3: Performance parameter configuration menu for AP.

The detailed information of an AP configuration is shown in figure 4.4.

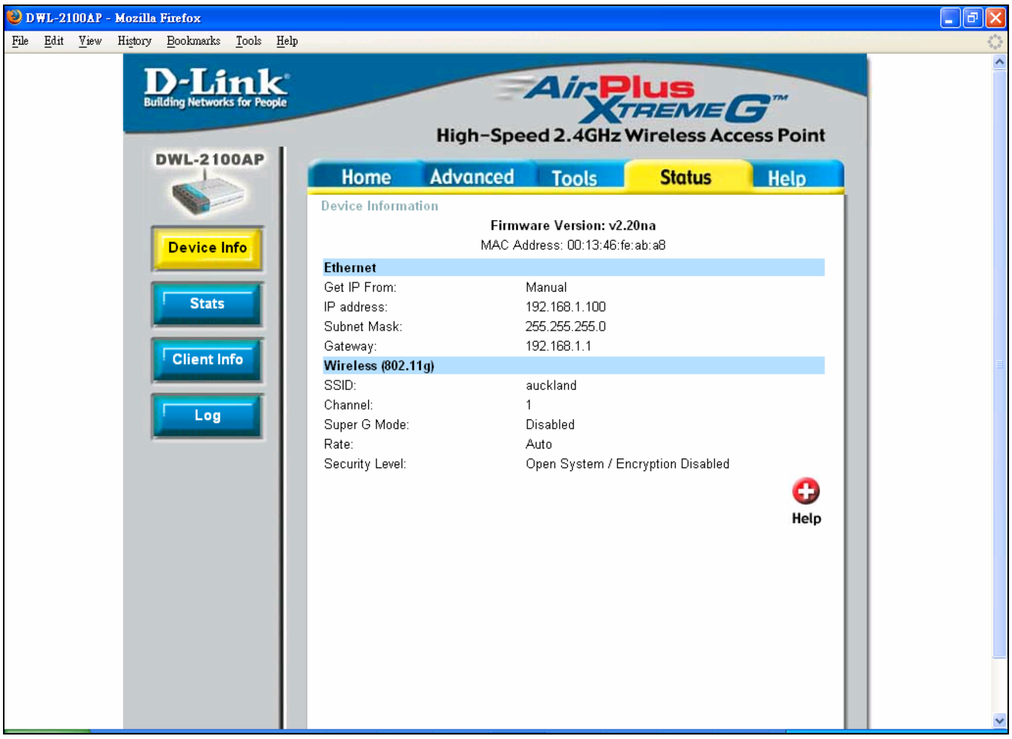


Figure 4.4: AP configuration information.

### 4.4.2 Wireless Adapter Configuration

The detailed configuration of a wireless adapter is shown below.

- SSID: Auckland
- Authentication: Open
- Wireless Mode: infrastructure
- Frequency: 802.11b/g 2.4 GHz
- Data Encryption: Disable
- Power Mode: Disable

Figure 4.5 and 4.6 show main configuration menu and performance parameter menu of D-Link DWL-G132 wireless adapter. The wireless adapter configuration must match with AP configuration in the infrastructure mode, so the wireless adapter configuration is based on AP configuration which we described in the previous section.

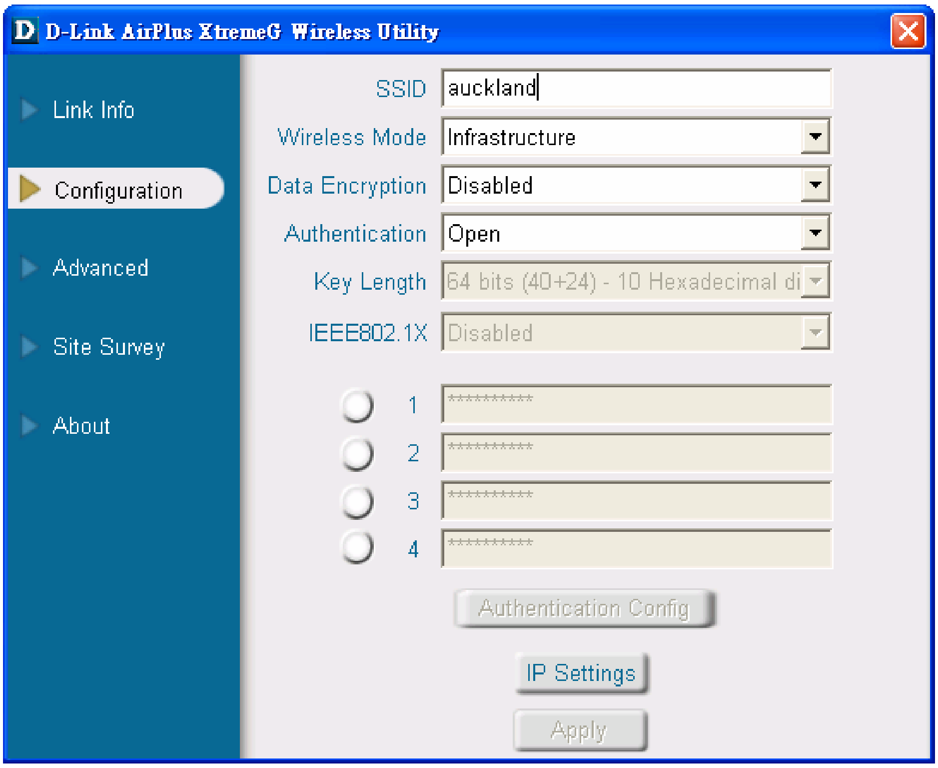


Figure 4.5: Main configuration menu for WLAN adapter.

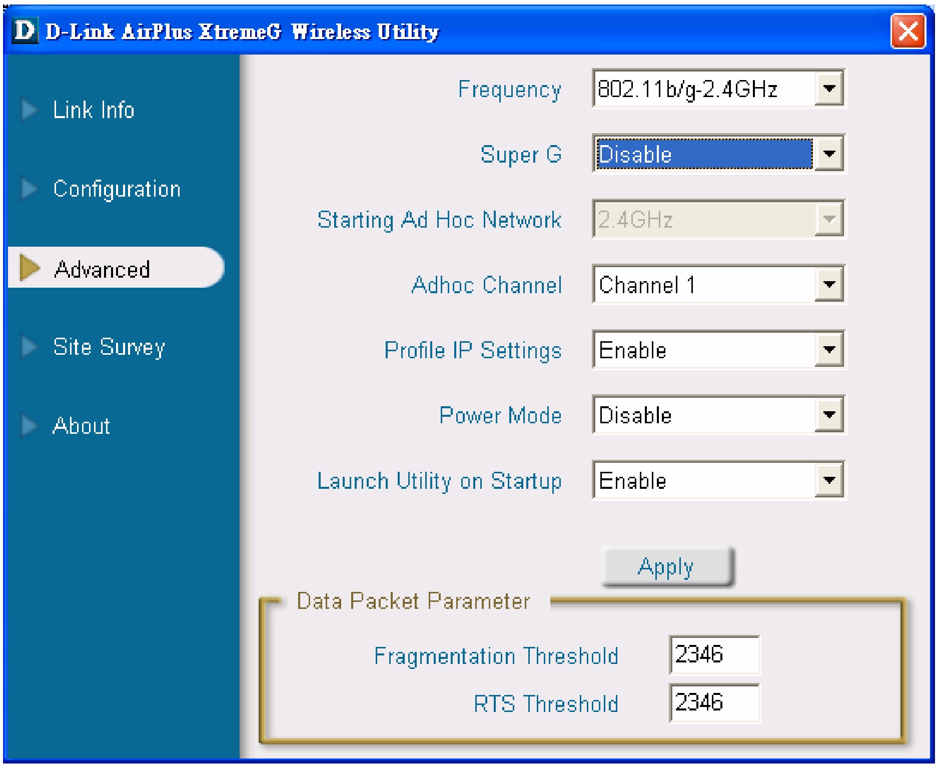


Figure 4.6: Parameter configuration menu for WLAN adapter.

The detailed information of a wireless adapter is shown in figure 4.7.

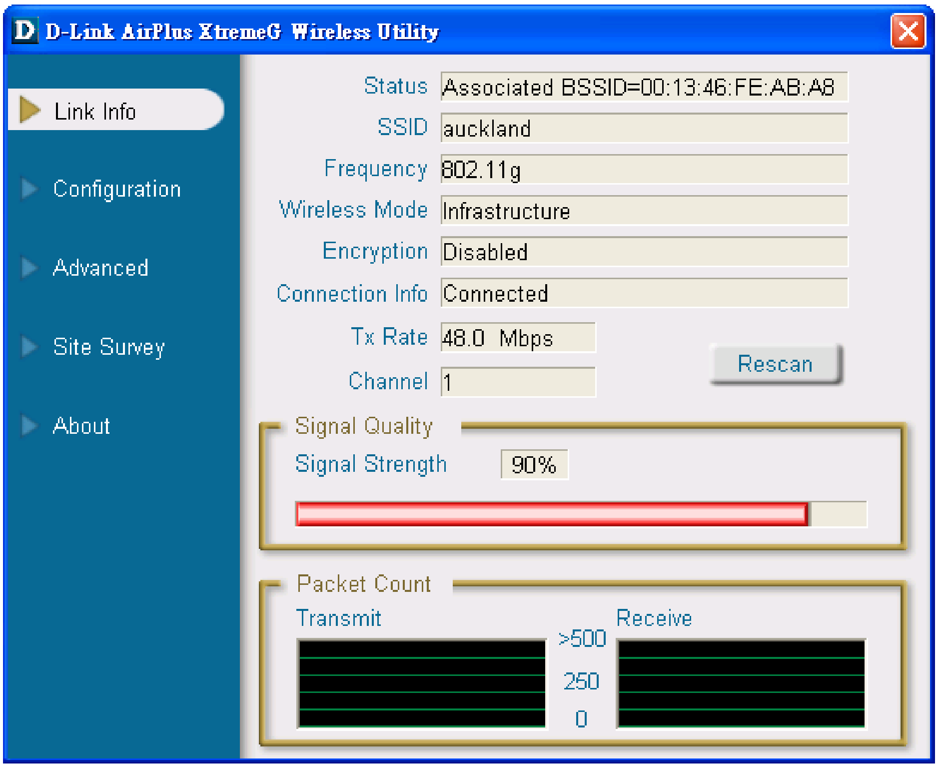


Figure 4.7: WLAN adapter configuration information.

### 4.4.3 AP Operation Mode

Two APs (D-Link DWL-2100AP) were used in the propagation measurements. The AP supports five different operation modes: AP Mode, WDS with AP Mode, WDS Mode, AP Repeater Mode, and AP Client Mode. Three of them (AP Mode, WDS with AP and WDS) were used in the propagation measurements. Figure 4.8 shows the operation mode configuration menu. There were no changes made to the current setting of the "AP mode". If the AP is configured as either "WDS with AP mode" or "WDS mode", the remote AP MAC address must be entered in the remote AP list.


Figure 4.8: AP operation mode configuration menu.

A brief description of the operating modes is given below.

- **AP Mode**

The role of an AP is as a coordinator in the AP mode. The AP receives data from wireless clients and forwards to other wireless clients or wired clients (via Ethernet).

- **WDS Mode**

In WDS mode, AP only provides a wireless bridge function. Wireless clients cannot associate with AP in WDS mode. WDS mode is a feasible solution when people would like to have wireless network connection between two or more buildings without a cable running through.

- **WDS with AP Mode**

In the WDS with AP mode, AP plays the role of a coordinator and wireless bridge. The AP offers AP mode and WDS mode functions.

## 4.5 Propagation Measurement Scenarios

The propagation measurement is divided into four phases: (1) preliminary measurement; (2) phase 1; (3) phase 2; and (4) phase 3. The detailed description of each phase and measurement scenarios are presented next.

### 4.5.1 Preliminary Propagation Measurement

The aim of preliminary measurement was to collect sample data to compare with the results of phase 1 to 3. Scenarios 1 to 5 were conducted in the meeting room under a controlled environment. In addition, scenario 6 was conducted to investigate the signal coverage and throughput without an AP in the obstructed office block.

- **Scenario 1**

The height of the transmitter (TX) and the receiver (RX) was placed 1 meter from the ground to avoid the Fresnel zone in all of the below mentioned propagation measurements. In addition, the propagation measurements were performed in the meeting room with different distances, different file sizes, and file formats in scenarios 1 to 5. A stopwatch was used to measure transmission time and WirelessMon software was used to measure RSS at RX in all of below measurement scenarios.

In figure 4.9, two laptops were configured as ad-hoc mode. The distance between laptops was set to 1, 2, and 3 meters. The experimental results of scenario 1 are presented in chapter 5 (section 5.1.1).

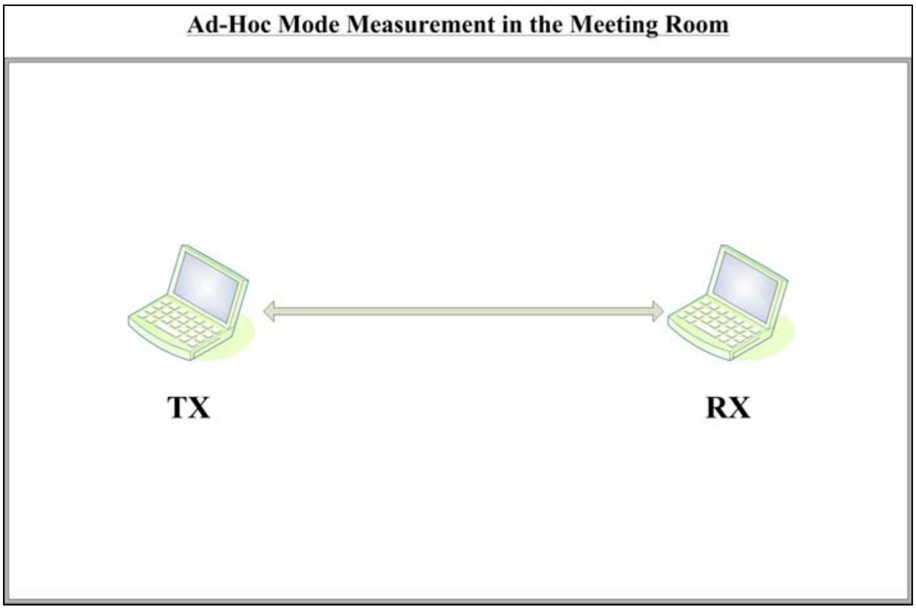


Figure 4.9: The ad-hoc mode measurement (scenario 1).

- **Scenario 2**

The height of APs was placed 1 meter from the ground in all of the below mentioned measurement scenarios. An AP was configured as “AP mode” and the throughputs were measured with different distances (1 and 2 meters) between the AP and laptops (as shown in figure 4.10).

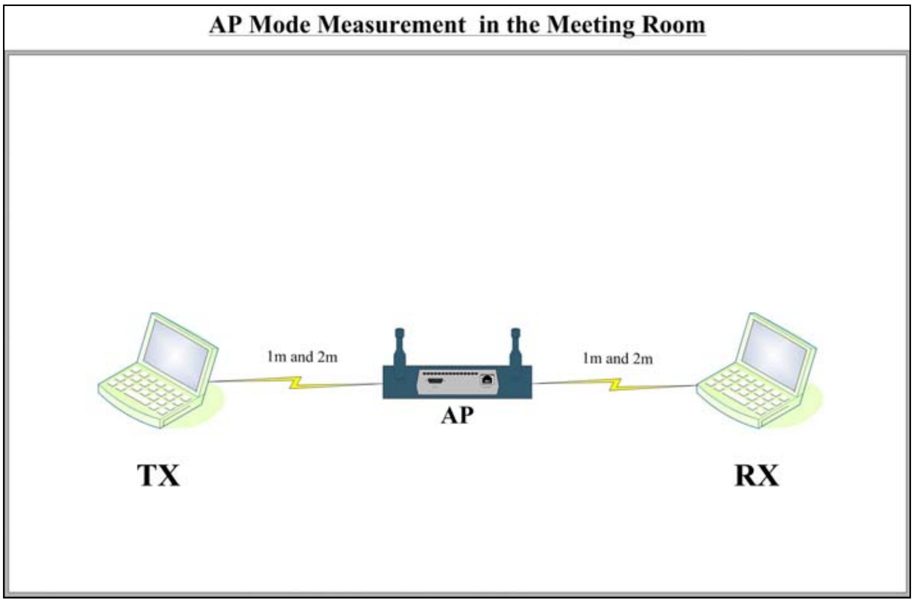


Figure 4.10: The AP mode measurement (scenario 2).

- **Scenario 3**

In figure 4.11, two APs were configured as “WDS with AP mode”.

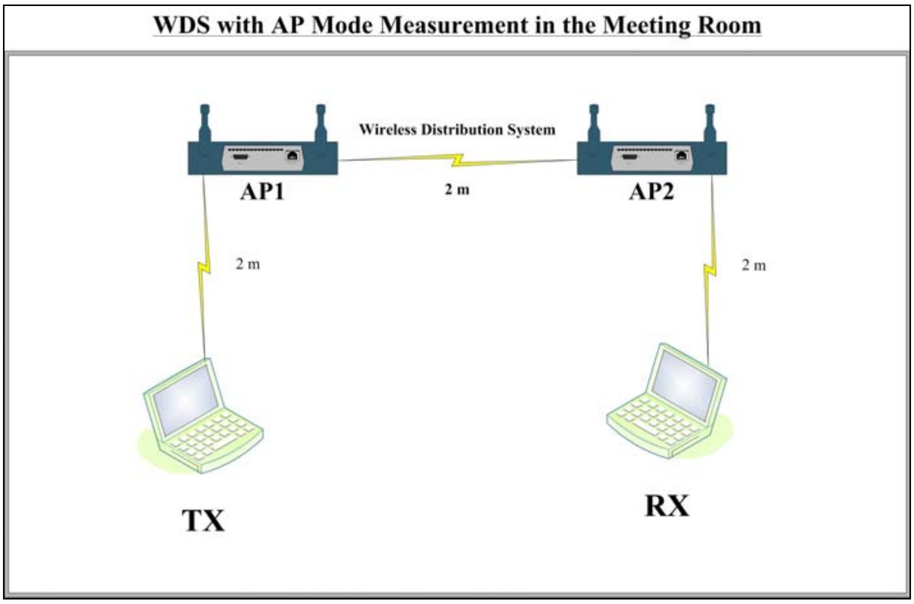


Figure 4.11: The WDS with AP mode measurement (scenario 3).

- **Scenario 4**

In figure 4.12, two APs were configured as “AP mode” and a Cat-5 cable was used to link two APs.

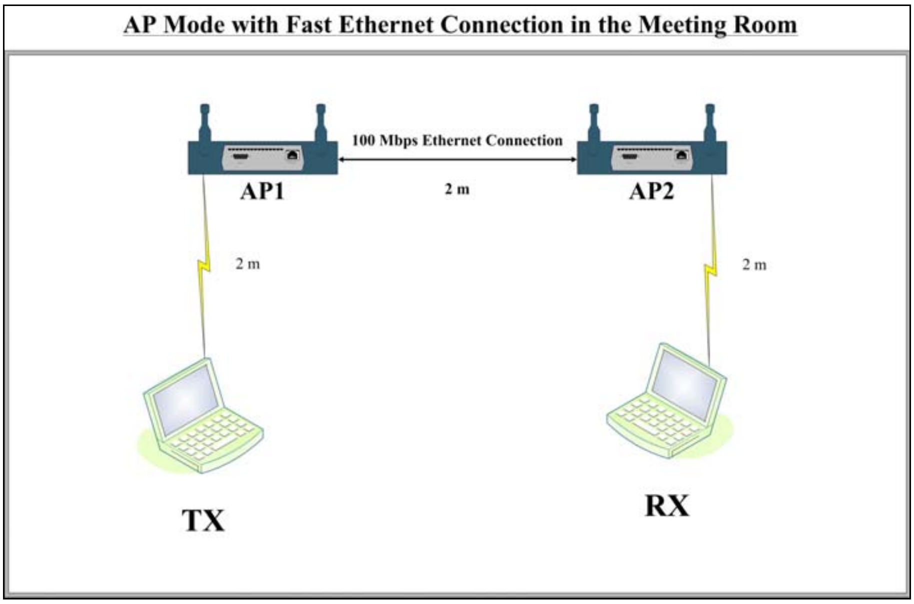


Figure 4.12: The AP Mode with Ethernet measurement (scenario 4).

- **Scenario 5**

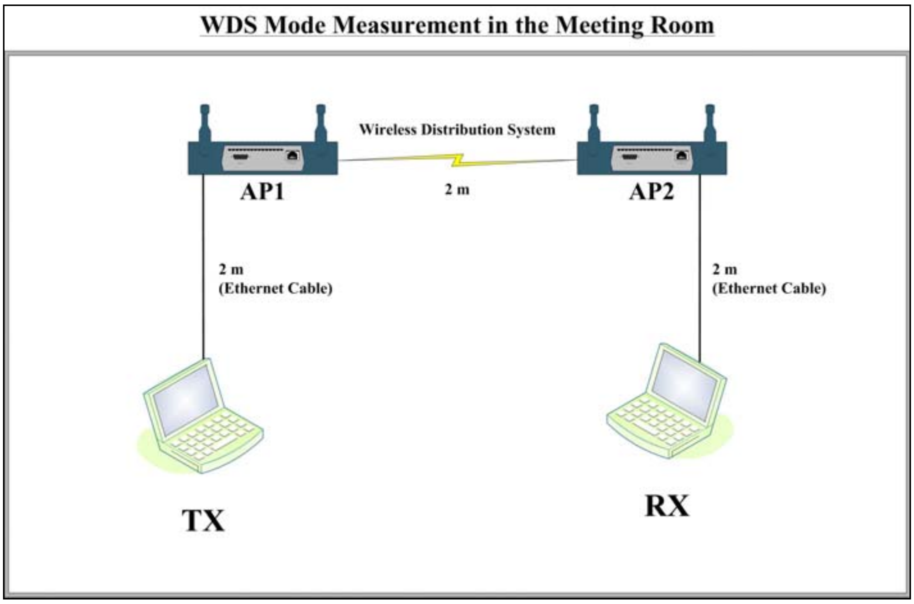


Figure 4.13: The WDS Mode measurement (scenario 5).

In figure 4.13, two APs were configured as “WDS mode”. Both TX and RX used Cat-5 cables to connect with APs.

By conducting scenario 2 to 5 experiments, we gained an insight into the relationship between file size, file format, distance, signal strength and throughput with different AP mode configurations. The experimental results of scenario 2 to 5 are presented in chapter 5 (section 5.1.2).

- **Scenario 6**

The ad-hoc mode measurement was performed in the obstructed office environment. TX was located at position “A” (as shown in figure 4.1). The position of RX was moved around the entire office to investigate the signal coverage and throughput. A data file (10.9 MB) was sent from TX to RX on each of RX location. By conducting scenario 6, we gained an insight into RSS, signal coverage and throughput without AP involved in the obstructed office block. The experimental results of scenario 6 are presented in chapter 5 (section 5.1.3).

### 4.5.2 Phase 1 Propagation Measurements

We configured an AP as “AP mode” for phase 1 propagation measurements. The more detailed description of phase 1 measurement is described next.

- **Scenario 7**

In figure 4.14, an AP was located at position “A” and TX was placed 2 meters away from the AP. Nineteen measurement points from A to S were defined in the office. Other than the nineteen measurement points, extensive measurements were also conducted in the corners and some areas of weak signal strength. For example, position

“(H-3.5m)F-H” is the measurement point which is 3.5 meters away from “H” and is between “F” and “H”.

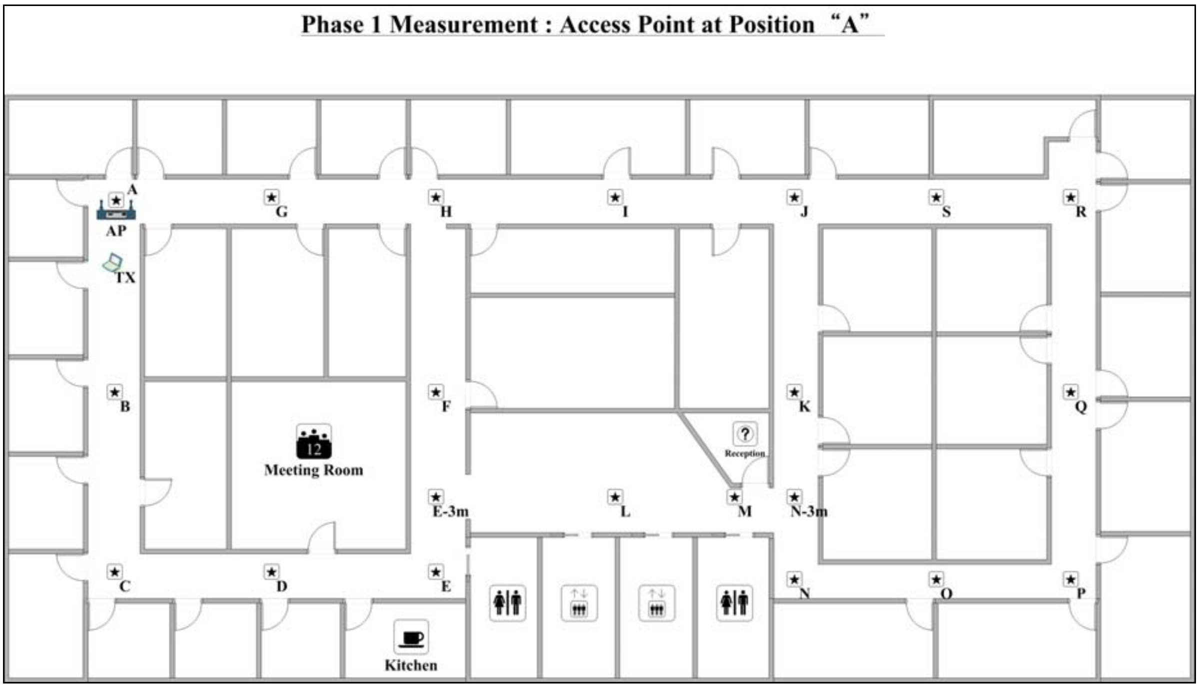


Figure 4.14: Phase 1 measurement: an AP at position “A”.

Eleven measurement points were selected for AP placement (A, F, G, H, I, J, K, L, R, E-3M, N-3M). TX was located 2 meters from the AP. A trolley was used to carry RX and RX was moved around all measurement points. A data file (10.9 MB) was sent from TX to RX in each measurement point, and a stopwatch was used to measure transmission time. The WirelessMon software was used to measure RSS at each RX location.

By conducting extensive experiments, we gained an insight into RSS and throughput of an AP placement in an obstructed office environment. The experimental results are presented in chapter 5 (section 5.2).

### 4.5.3 Phase 2 Propagation Measurements

Two APs were configured as "WDS with AP mode" and "AP mode" with Ethernet connection. The detailed description of phase 2 measurement is described next.

- **Scenario 8**

Two APs were configured as "WDS with AP" mode. Figure 4.15 shows a measurement scenario with two APs at positions "A" and "J" and TX and RX were placed 2 meters away from APs. Three large files of 250 MB with different formats (data, audio and video format) were sent from the TX to the RX. A stopwatch was used to measure the transmission time. In the remaining of phase 2 measurements, two APs were placed at "A and R", "G and J", "G and R", and "E-3M and N-3M".

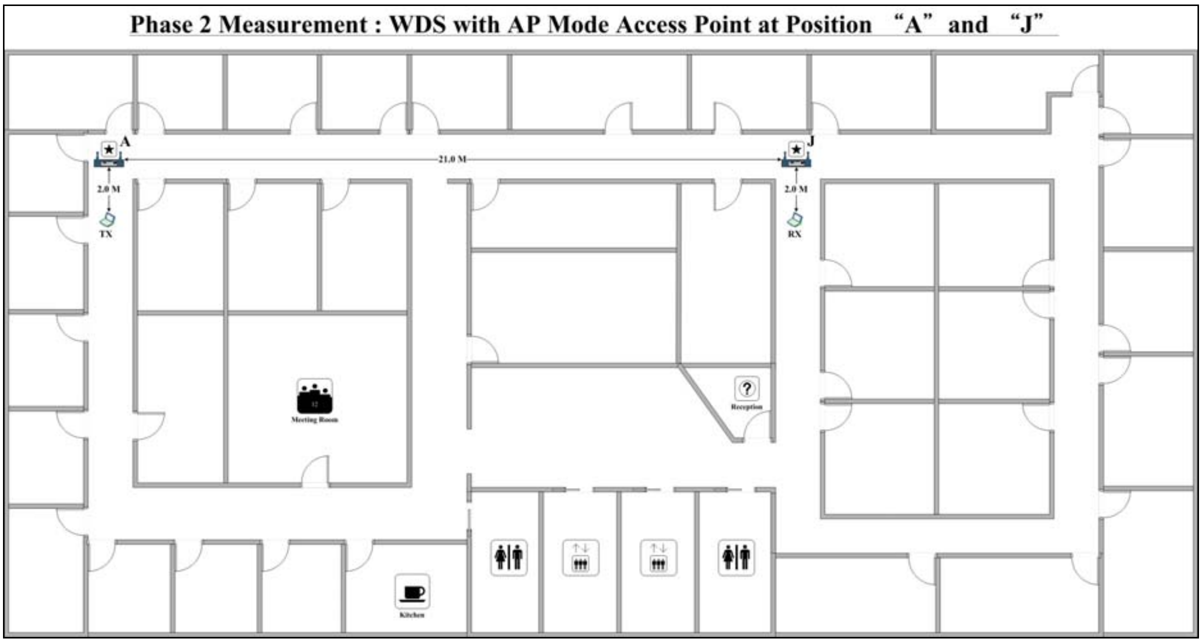


Figure 4.15: Phase 2 measurement: APs at position "A" and "J".

- **Scenario 9**

The scenario 9 repeated the procedure of scenario 8 with the following changes: the two APs were configured as "AP mode" and placed at position "E-3M and N-3M" and a Cat-5 cable was used to link two APs (as shown in figure 4.16).

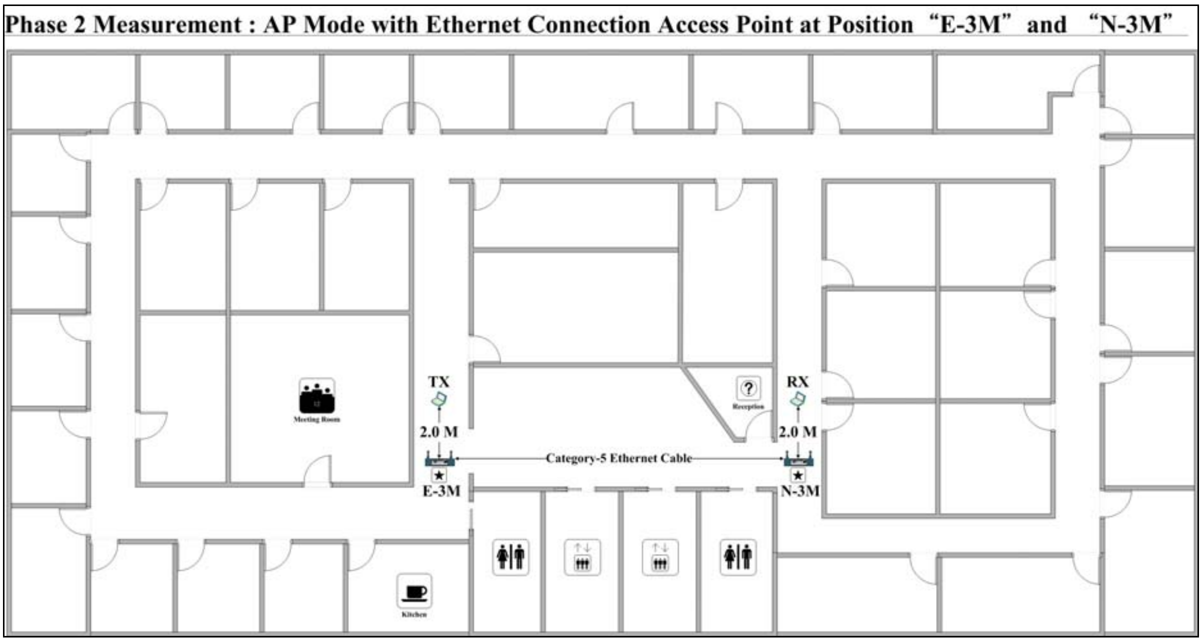


Figure 4.16: Phase 2 measurement: APs at position "E-3M" and "N-3M".

By conducting phase 2 experiments, we gained an insight into the throughput performance of multiple APs in the obstructed office environment. The experimental results of both the scenarios 8 and 9 are presented in chapter 5 (section 5.3).

### 4.5.4 Phase 3 Propagation Measurements

We obtained two optimal positions for APs placement from phase 2 propagation measurements. Apparently, the positions (E-3M and N-3M) had better performance than other positions. Therefore, we placed APs at position "E-3M" and "N-3M". The detailed description of phase 3 measurement is described next.

- **Scenario 10**

We configured APs as WDS with AP mode and placed APs at "E-3M" (SSID: Auckland) and "N-3M" (SSID: Wellington). In the first measurement, we placed TX 2 meters away from the AP (SSID: Auckland) and TX was associated with the AP (SSID: Auckland).

On the other hand, RX was associated with the AP (SSID: Wellington). We used a trolley to carry RX and moved RX at measurement points "K, N, O, P, Q, R and S". A data file (153.6 MB) was sent from TX to RX and a stopwatch was used to measure transmission time. The WirelessMon software was used to measure RSS at all measurement points. The same was repeated as a second measurement with TX associated and placed 2 meters away from the AP (SSID: Wellington). RX was associated with an AP (SSID: Auckland) and measured at points "A, B, C, D, E, F, G, H and I".

- **Scenario 11**

Scenario 11 repeated the procedure of scenario 10 with the following changes: the two APs were configured as AP mode and a Cat-5 cable was used to link two APs.

By conducting phase 3 experiments, we gained an insight into the relationship of RSS and throughput when two APs were deployed in the obstructed office environment. The experimental results of scenarios 10 and 11 are presented in chapter 5 (section 5.4).

## 4.6 Measurement Accuracy

The propagation measurement can be a time consuming and tedious work. It was considered some potential issues to reduce unexpected interference and to improve the measurement accuracy.

- **Interference from human movement**

The experimental floor area used for the propagation measurement is usually very busy during weekdays due to the fact that it is occupied by more than 30 staff members. We performed the propagation measurements during weekends to avoid any sort of hindrance.

- **Co-channel Interference**

With wide deployment of WLAN, three to five APs can be found within the range of measurement. Scanning and adjusting the radio channel prior to experiment was done to prevent co-channel interference.

- **Parameter Setting**

We turned off data encryption function and used the default setting of AP and wireless network adapter to reduce overhead and interference from AP configuration. The configuration of APs and wireless adapters is described in section 4.4.1 and 4.4.2.

## 4.7 Summary

The detailed experimental design for propagation measurement is presented. The preliminary measurement would help us to understand AP configuration and characteristics of WLAN. We also identified the sufficiency of one AP deployment in the office from phase 1 measurement. By performing phase 2 measurement, inter-APs throughput and optimal position placements of APs were derived. We gained knowledge and understanding of the signal coverage and throughput of two APs deployment from phase 3 measurement. Finally, we believe that careful experimental design would save time and enhance the accuracy of experimental results.

# Chapter 5

# Results and Discussion

The hardware and software requirements, AP configurations, and measurement scenarios for the propagation study have been discussed in chapter 4. In this chapter, the preliminary results are presented in section 5.1, and phase 1 to 3 results are discussed in section 5.2, 5.3 and 5.4, respectively. The capacity estimation of WLAN is also discussed in section 5.5. Various recommendations for AP deployment are discussed in section 5.6, and the chapter concludes with a brief summary in section 5.7.

## 5.1 Preliminary Measurement Results

The preliminary throughput measurements of both an ad-hoc and the infrastructure modes were performed under controlled environment to obtain the saturation throughput of AP and wireless adapter. We used the results of preliminary measurement to compare the results of phase 1 to 3. The detailed numerical results are presented in appendix A.

The receiver sensitivity is an important factor in determining the data rate of Wi-Fi networks. Table 5.1 illustrates the relationship of receiver sensitivity and data rate according to specification of WLAN adapter (refer appendix E). As mentioned in [94], the IEEE 802.11b throughput is around 5 Mbps and 802.11g throughput is 11 Mbps under normal operating and low traffic condition. The throughput of 802.11b (5 Mbps) is 45% of the theoretical data rate (11 Mbps), while the throughput of 802.11g (11 Mbps) is only 20% of the theoretical data rate (54 Mbps). Therefore, the estimated throughput as shown in table 5.1 is calculated as follows:

*Estimated Throughput of 802.11g = Data Rate * 20%* – (5.1)

*Estimated Throughput of 802.11b = Data Rate * 45%* – (5.2)

| | ***Receiver Sensitivity (dBm)** | ***Data Rate (Mbps)** | **Estimated Throughput (Mbps)** |
|---|---|---|---|
| **802.11b** | -82 | 11 | 5 |
| **802.11b** | -87 | 2 | 0.9 |
| **802.11g** | -88 | 6 | 1.2 |
| **802.11g** | -86 | 9 | 1.8 |
| **802.11g** | -84 | 12 | 2.4 |
| **802.11g** | -82 | 18 | 3.6 |
| **802.11g** | -78 | 24 | 4.8 |
| **802.11g** | -74 | 36 | 7.2 |
| **802.11g** | -69 | 48 | 9.6 |
| **802.11g** | -66 | 54 | 11 |

Table 5.1: Receiver sensitivity, theoretical data rate and estimated throughput.

* Receiver sensitivity and data rate are retrieved from specifications of WLAN adapter. For further information, please refer appendix E.

Table 5.1 shows that once the receiver sensitivity is larger than -88 dBm, the WLAN adapter can receive data under the IEEE 802.11g standard. Moreover, when RSS is larger than -66 dBm, the WLAN adapter reaches maximum data rate (54 Mbps). The table provides an important reference to facilitate the discussion.

### 5.1.1 Scenario 1: The Ad-Hoc Mode in the Meeting Room

Two IEEE 802.11g wireless adapters (D-Link DWL-G132) were used in the experiment. However, we would like to emphasize the point before arriving at the results section that the adapter only supports 802.11b with maximum data rate at 11Mbps in the ad-hoc mode.

The two laptops had better performance and signal strength when kept 2 meters apart than being kept distant by 1 meter (as shown in figure 5.1). This is because if two wireless stations are placed too close, it would cause path loss. Numerical results are presented in appendix A (table A.1).

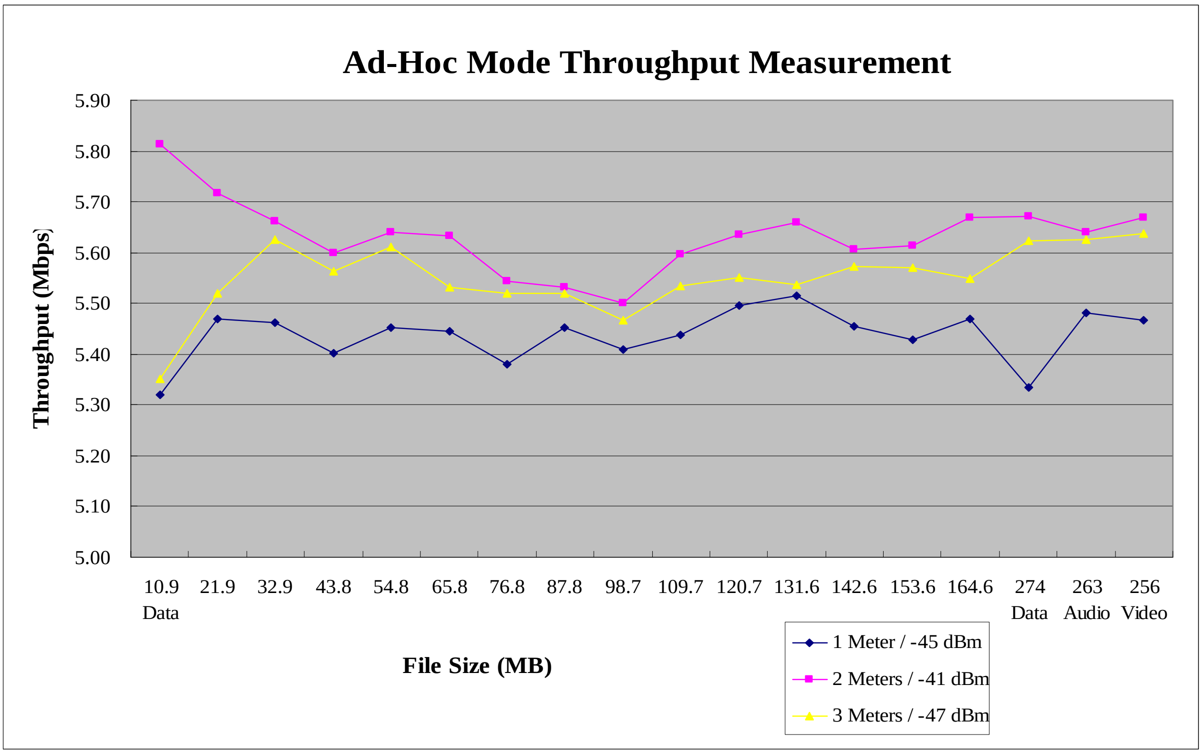


Figure 5.1: Throughput measurement under ad-hoc mode.

In table 5.1, the estimated throughput of IEEE 802.11b is 5 Mbps, once the receiver sensitivity is large than -82 dBm. Our measurement throughput (average throughput 5.5 Mbps) with RSS (-41 dBm) was slightly better than estimated throughput.

As mentioned in [49], theoretical maximum user datagram protocol (UCP) throughput of the IEEE 802.11b is 5.12 Mbps as well as 2.74 Mbps for TCP throughput with large packet size (1024 bytes) without RTS/CTS. In addition, [95] depicts that two wireless stations were configured in the direct line-of-sight (LOS) with the throughput of 802.11b (5 Mbps). Comparing the results with [49] and [95], our measurement results were very close to the theoretical UDP throughput (5.12 Mbps) and the real-world measurement throughput (5 Mbps). Our measurement results were better than the theoretical results in [49] and the results of crowded office experiment in [95]. The possible reason is that our measurements were conducted under controlled environment.

### 5.1.2 Scenario 2 to 5: The Infrastructure Mode in the Meeting Room

We conducted measurements in the meeting room and configured an AP as “AP mode” in scenario 2, two APs as “WDS with AP mode” in scenario 3, two APs as “AP mode” with Ethernet connection in scenario 4, and two APs as “WDS mode” in scenario 5.

Figure 5.2 shows throughput with different AP configurations. Detailed numerical results are presented in appendix A (table A.2 to A.6). In the “AP mode”, the average throughput is 10.357 Mbps (refer table A.6) when laptops were placed 2 meters away from the AP. However, when the laptops were placed only 1 meter away from the AP, the average throughput is dropped by 21% (8.157 Mbps). Similarly, in the ad-hoc mode the throughput was 5.437 Mbps and 5.634 Mbps at 1m and 2m respectively (refer table

A.1). Again, the results indicated that when two wireless nodes were too closely located, it resulted in lower RSS and throughput.

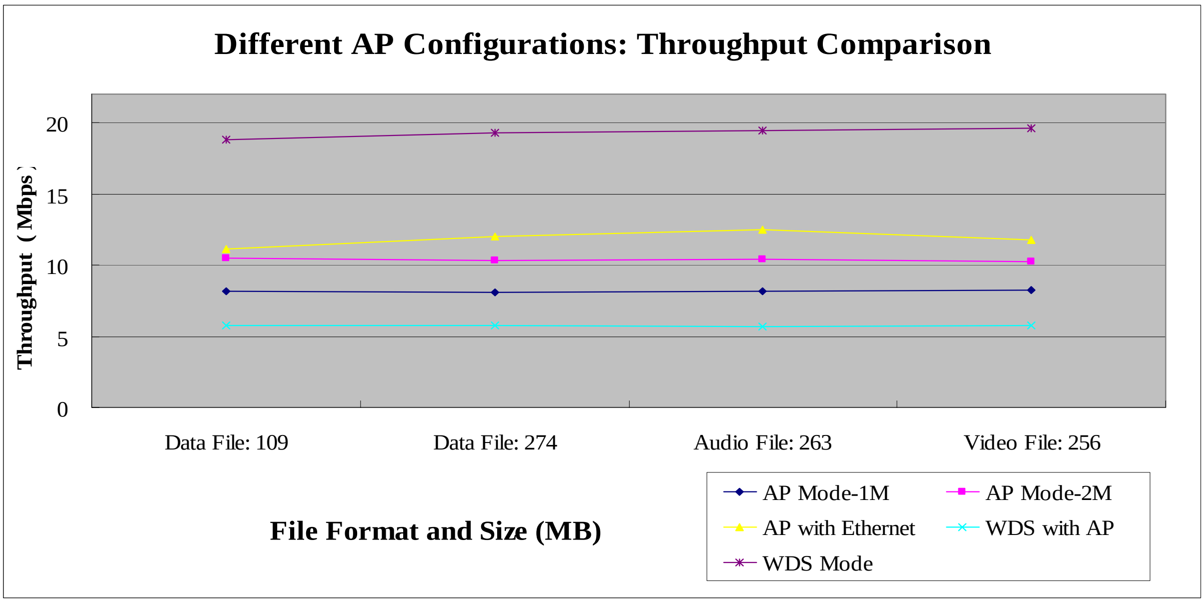


Figure 5.2: Throughput comparison with different AP configurations.

As mentioned in [71], APs can reach their maximum throughput with a certain file size. Initially, throughputs will keep increasing along with an increased transferred file size until it reaches the maximum capacity of the AP. However, our measurement results indicate that there is no apparent change of throughput with different file sizes. The possible reason is that behavior of AP varies with different models and vendors.

We also found that the file format did not make a significant impact on throughput. For example, a throughput of 10.306 Mbps (refer table A.2) was obtained on a 274 MB data file, while a throughput of 10.236 Mbps was obtained on a 256 MB video file.

The throughput under the “WDS with AP mode” was lower (average throughput: 5.755 Mbps, refer table A.6) than the “AP mode” (10.357 Mbps) and the “AP mode” with

Ethernet connection (11.863 Mbps). If a Cat-5 Ethernet cable is used instead of WDS, throughput can be improved around 103% (from 5.755 to 11.863 Mbps).

The average throughput of “WDS mode” (19.281 Mbps, refer table A.5) was much better than other AP configurations. However, “WDS mode” only supports the point-to-point connection. Wireless clients cannot associate with the AP in WDS mode.

### 5.1.3 Scenario 6: The Ad-Hoc Mode in the Office

Figure 5.3 shows the relationship of throughput, RSS, and distance coverage under an ad-hoc mode measurement with LOS condition. The average throughput was 5.507 Mbps and RSS was around -43 to -67 dBm (refer table A.7).

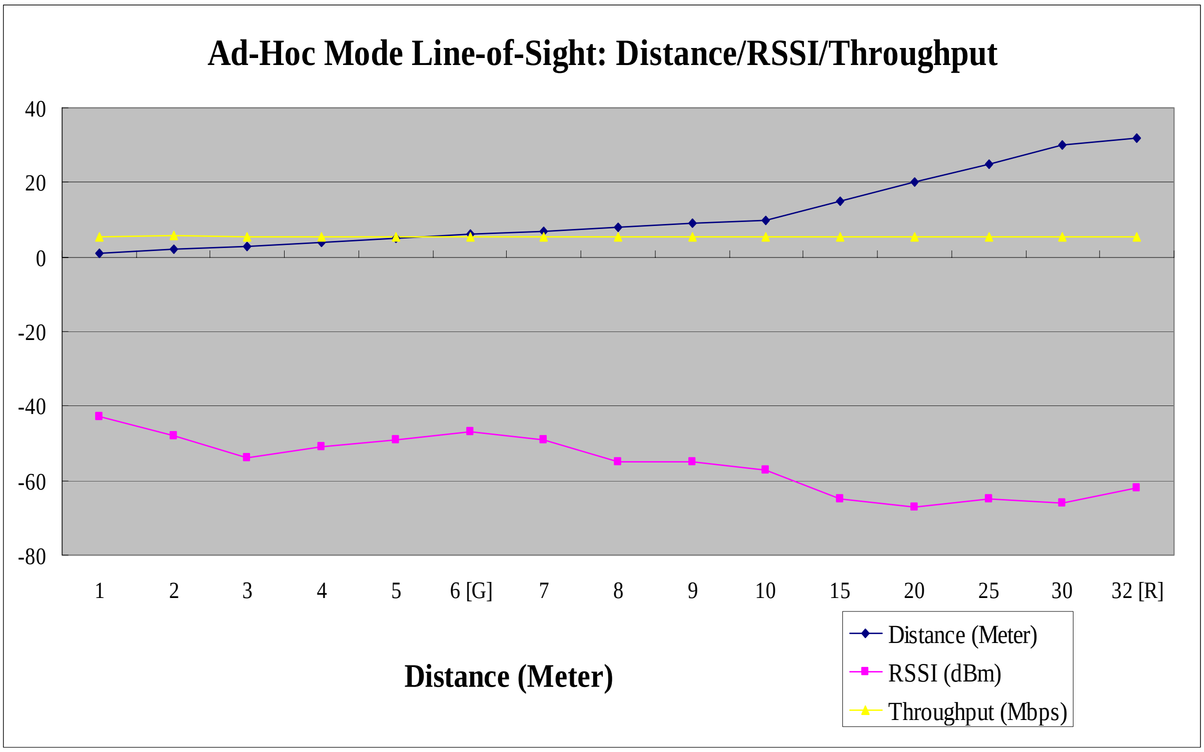


Figure 5.3: The ad-hoc mode measurement with LOS in the office of WY building.

Because the received signal threshold of WLAN adapter was -82 dBm at 11 Mbps (refer table 5.1), the impact of distance and signal strength on throughput were little in LOS condition in the office. However, due to attenuation, signal strength was getting weaker with longer distance (for example, 1m: -43dBm to 20m: -67 dBm, refer table A.7).

In figure 5.4, signal strength and throughput dropped significantly when RX was far away from TX and obstructions were located between RX and TX. Furthermore, signal was blocked in the small area of the office (for example, nearby measurement point "P"). Therefore, ad-hoc mode is an inappropriate solution for WLAN deployment in this office. An AP should be used to boost signals.

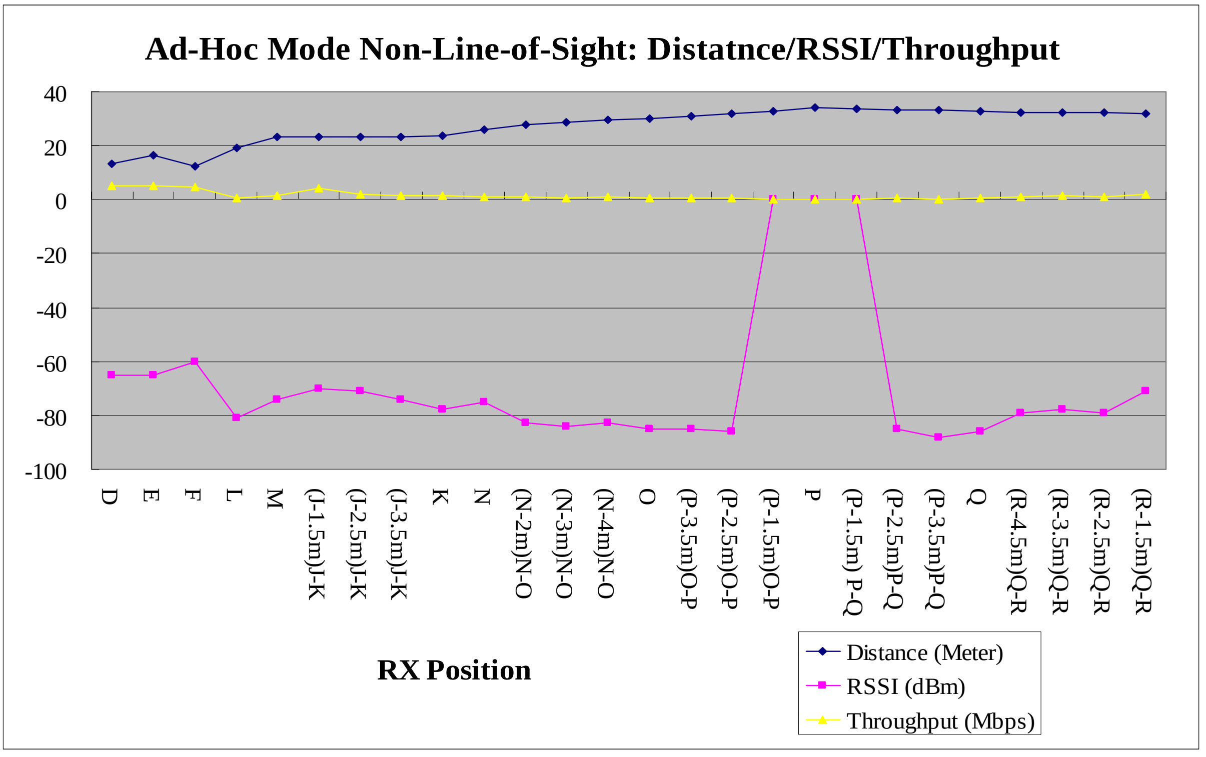


Figure 5.4: The ad-hoc mode measurement with NLOS in the office of WY building.

We have collected rich experimental data under various AP configurations. The important conclusion of preliminary measurement is that the ad-hoc mode does not have sufficient signal coverage and throughput in the obstructed office environment under consideration. Indeed, one or more APs should be deployed to provide sufficient signal coverage and throughput in the office.

Three phases of measurements are described next.

## 5.2 Phase 1 Measurement

The phase 1 measurement aims to investigate the impact of signal strength on Wi-Fi link throughput and to build up a rich database (signal strength and throughput) with a single AP placement. The measurement results are presented in section 5.2.1 with different positions of AP placement. We provide a detailed throughput analysis and discussion in section 5.2.2.

### 5.2.1 Results and Discussion

The measurement results are presented in three forms, such as: (1) numerical results; (2) curve diagram; and (3) throughput map. The numerical results of distance, RSS, and throughput are presented in the form of tables in appendix B (for example, table B.1). The relationship of throughput, signal strength and distance are shown by curve graphs (for example, figure 5.5) and throughput maps (for example, figure 5.6).

The detailed definition of measurement point is shown in figure 4.1. The notation of measurement point is presented alphanumerically. For example, “(P-3.5m)O-P” is to present the measurement point which is located at 3.5 meters away from measurement point “P” and between measurement points “O” and “P”.

## AP at Position "A"

Figure 5.5 shows propagation measurement results of distance, RSS and throughput when the AP was located at position "A". RSS and throughput were sufficient between measurement points "B" and "I". However, RSS and throughput were decreasing from measurement point "L", because of the number of obstructions and distance were increasing between the AP and RX. RSS of measurement points "O" was the lowest (-90 dBm, refer table B.1). Although measurement points "O" were not the furthest point from the AP, some obstructions were located between the AP and RX, resulting in the lowest RSS and throughput (0.393 Mbps, refer table B.1) at measurement point "O".

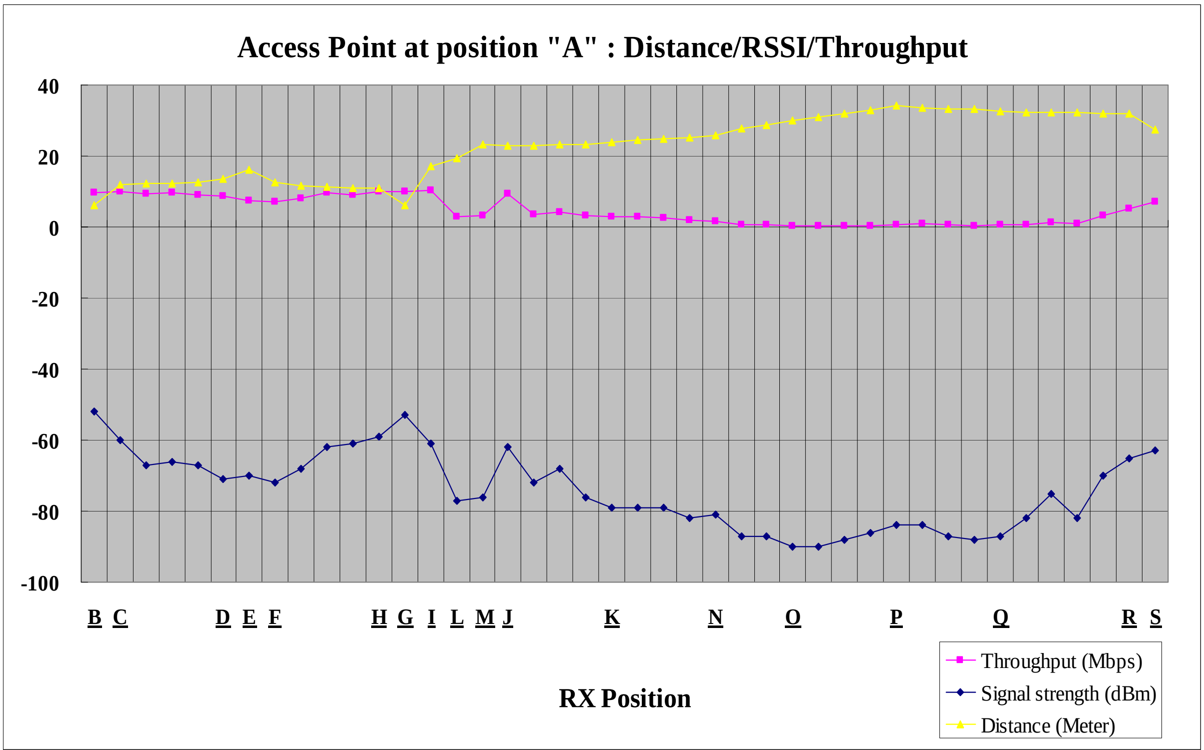


Figure 5.5: Distance/RSSI/Throughput for AP at position "A".

We found that RSS had significant impact on Wi-Fi link throughput. For example, RSS at measurement point "H" was -59 dBm with throughput 10.088 Mbps (refer table B.1). When RSS was -76 dBm at "M", the throughput was only 3.134 Mbps. In general, throughput decreases along with lower RSS. In fact, the change of throughput was not only determined by RSS, but also by other factors. These factors will be discussed later in this section.

The real throughput in the obstructed office environment is shown in the form of a map (as shown in figure 5.6). The various colors were used to demonstrate different throughputs, for example, lower throughput (0~2 Mbps) between measurement points “N” and “R” was presented by the color tan.

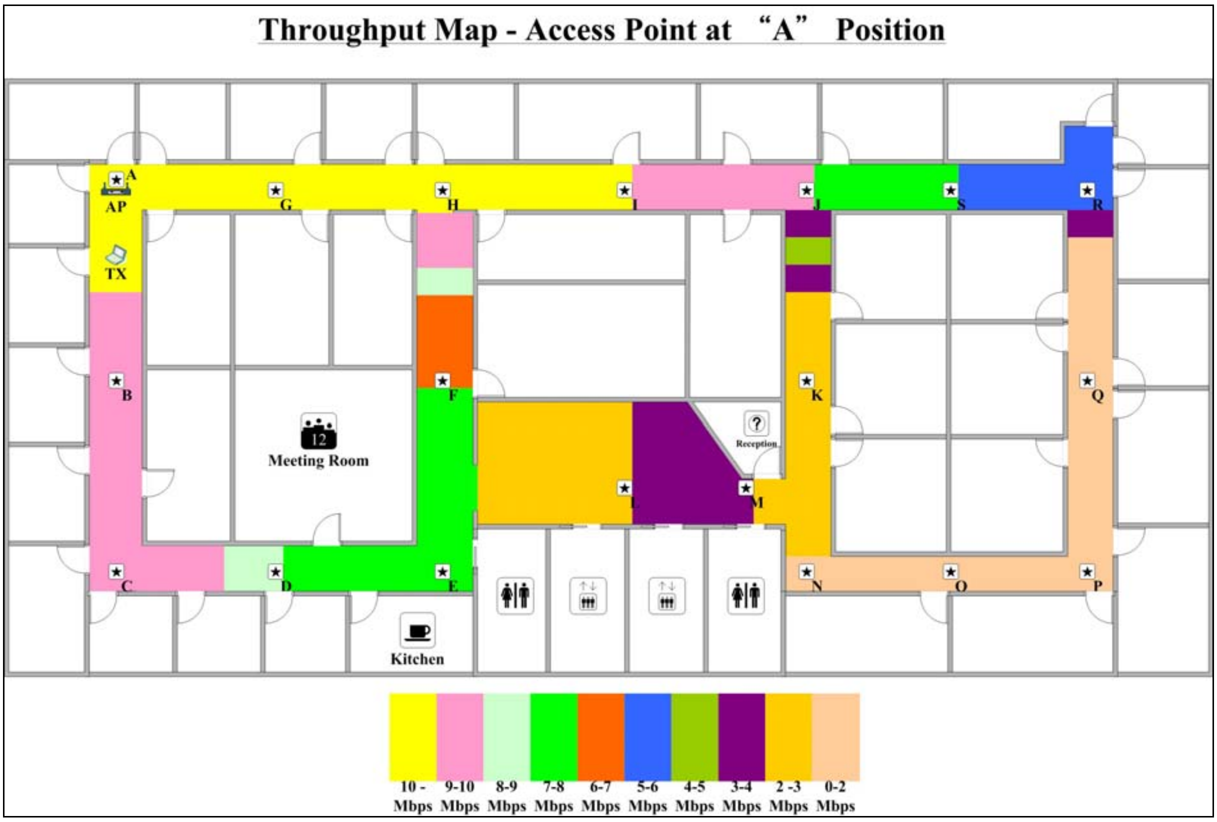


Figure 5.6: Throughput map for AP at position “A”.

In figure 5.6, overall throughput was better on the “left-hand side” of the office and the center of the office. The throughput of “right-hand side” of the office was very low. However, due to no obstructions between AP and measurement points “R” and “S”, the throughput and RSS were acceptable at measurement points “R” and “S”.

The throughput map clearly demonstrates that when AP was located at position “A”, it could not offer sufficient throughput for the entire office. Moreover, the throughput map is another way to represent the measurement results. The throughput map serves as a guide to know the actual throughput at different locations in the office and is more accurate to demonstrate WLAN performance than RSS.

## AP at Position “G”

Figure 5.7 shows the results of distance, RSS and throughput when the AP was located at position “G”. Overall, RSS and throughput was adequate between measurement points “A” and “I”. For example, RSS at “H” was -55 dBm and throughput 10.971 Mbps (refer table B.2). Comparing with the estimated throughput (11 Mbps, refer table 5.1) the measurement result was very close to the estimated throughput.

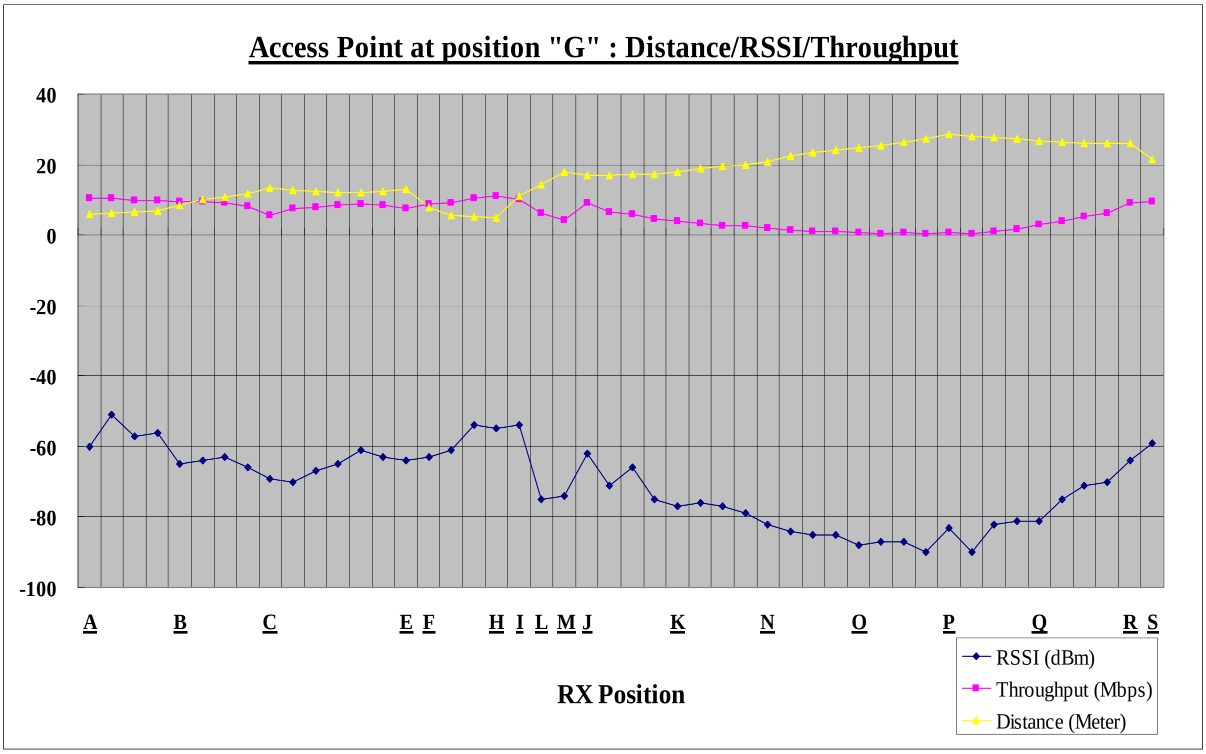


Figure 5.7: Distance/RSSI/Throughput for AP at position “G”.

In table 5.1, when RSS is larger than -66 dBm, the data rate is 54 Mbps and the estimated throughput is 11 Mbps. However, our measurement results showed that many measurement points had better RSS (large than -66 dBm), but not higher throughput. For example, RSS at measurement point “E” was -64 dBm and the measurement throughput 7.632 Mbit/s. It was 31% lower than the estimated throughput. The results revealed that we cannot only rely on RSS to determine the WLAN performance.

Figure 5.8 shows throughput map of the AP when it was placed at position “G”. The overall throughput was sufficient on the “left-hand side” of the office. However, the throughput was lower on the “right-hand side” of the office. Furthermore, compared to figure 5.6, the area of lower throughput is smaller. It means that when AP was located at position “G”, it would offer better throughput than AP at position “A” for the “right-hand side” of the office.

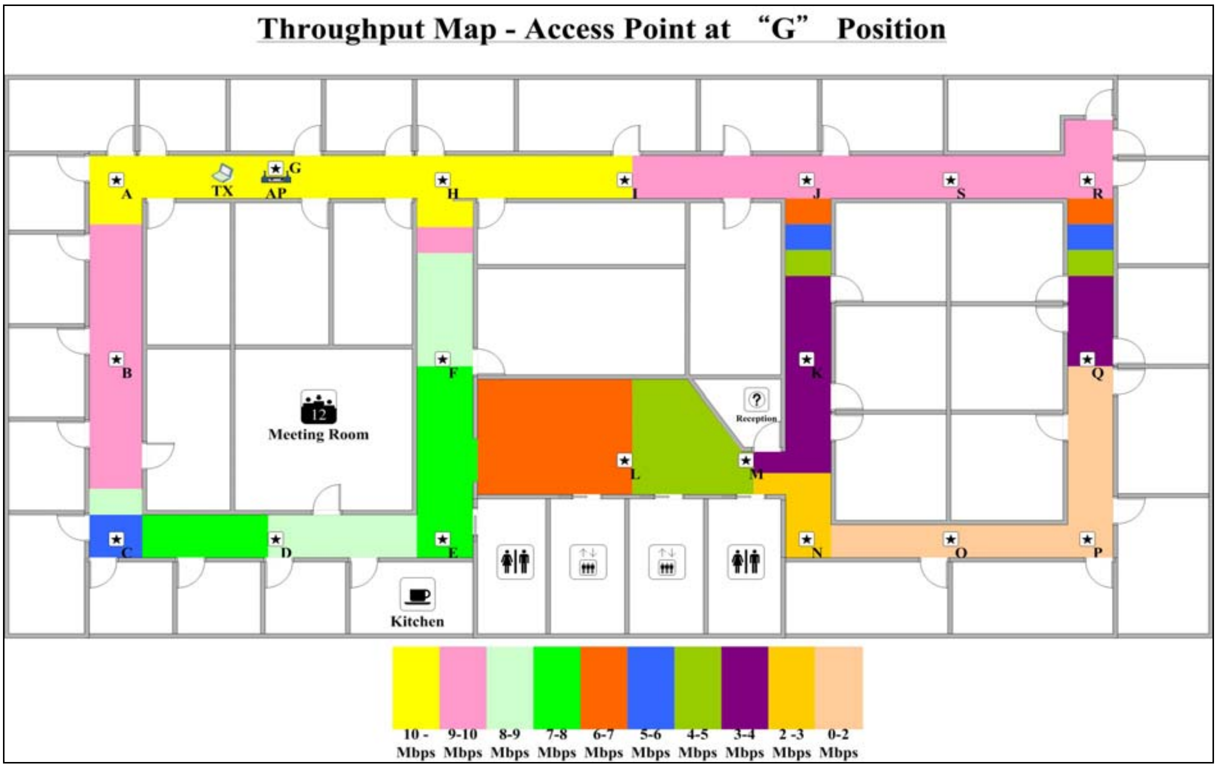


Figure 5.8: Throughput map for AP at position “G”.

## AP at Position "E-3M"

Figure 5.9 shows the measurement results of distance, RSS and throughput when the AP was located at position "E-3M". With different AP locations, RSS and throughput may also change at the same time. For example, RSS of measurement point "(C-2m)C-D" was -63 dBm with a throughput of 10.325 Mbps when the AP was located at position "E-3M" (refer table B.3). In the previous scenario (AP at position "G") at the same measurement point "(C-2m)C-D", RSS was -70 dBm with a throughput of 7.566 Mbps (refer table B.2). The results revealed that position of AP has an important impact on RSS and throughput.

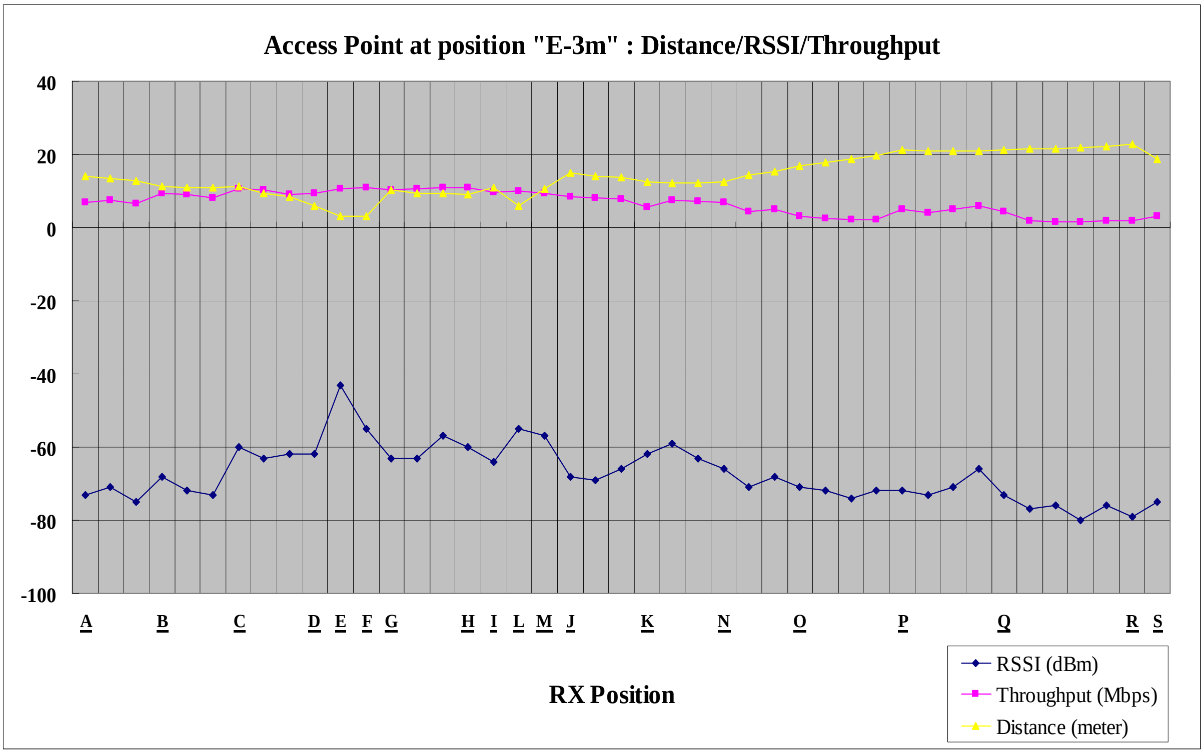


Figure 5.9: Distance/RSSI/Throughput for AP at position "E-3M".

Figure 5.10 shows throughput map of the AP when it was placed at position "E-3M". The throughput was adequate on the "left-hand side" and the center of the office. However, throughput is still quite low in the corner of the "right-hand side" of the office (for example, measurement point “R”).

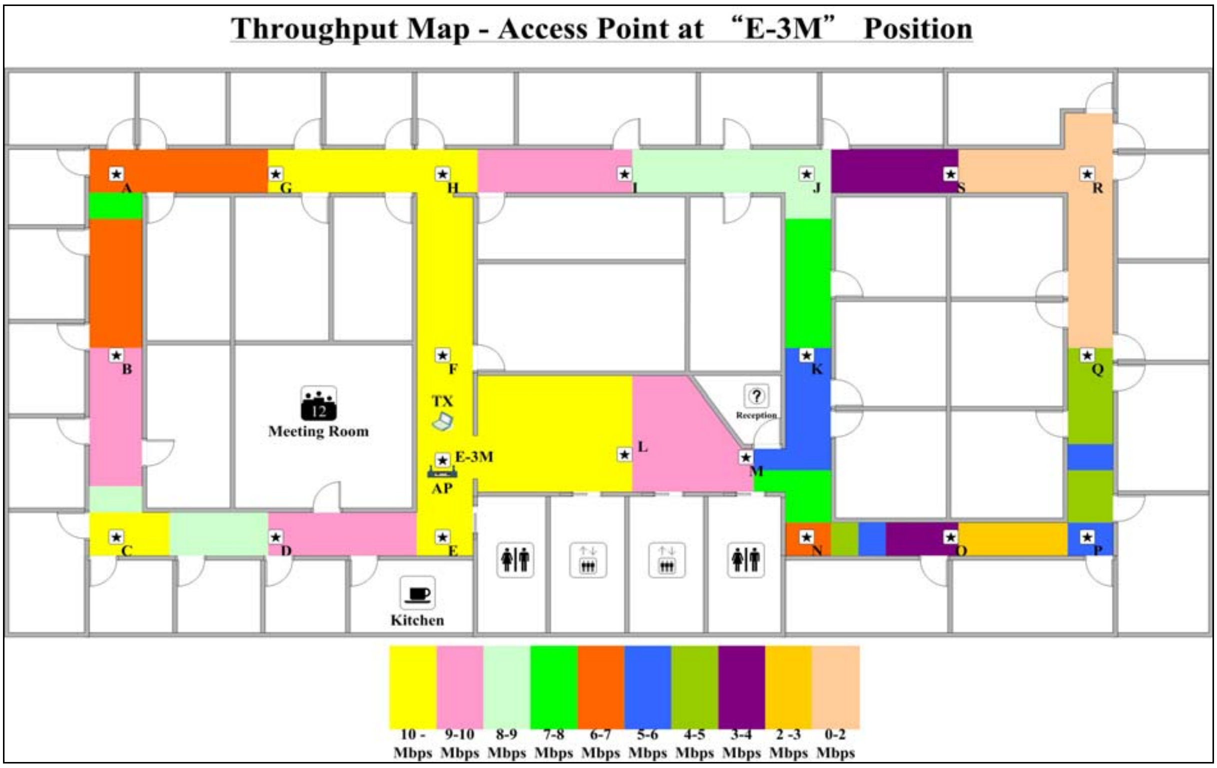


Figure 5.10: Throughput map for AP at position “E-3M”.

## AP at Position “J”

Figure 5.11 shows the results of distance, RSS and throughput when the AP was located at position “J”. With same RSS and longer distance to AP, the measurement point “H” (10.205 Mbps, 12 meters, refer table B.4) had better throughput than measurement point “L” (7.767 Mbps, 10.82 meters). The reason is that measurement point “H” was located in the direct LOS to the AP, but measurement point “L” was located in the NLOS to the AP. The results revealed that the number of obstructions had a considerable impact on the throughput.

In figure 5.12, the throughput was quite lower in the corner of the “left-hand side” of the office (for example, measurement point “C”), but overall throughputs were sufficient on the “right-hand side” and the center of the office.

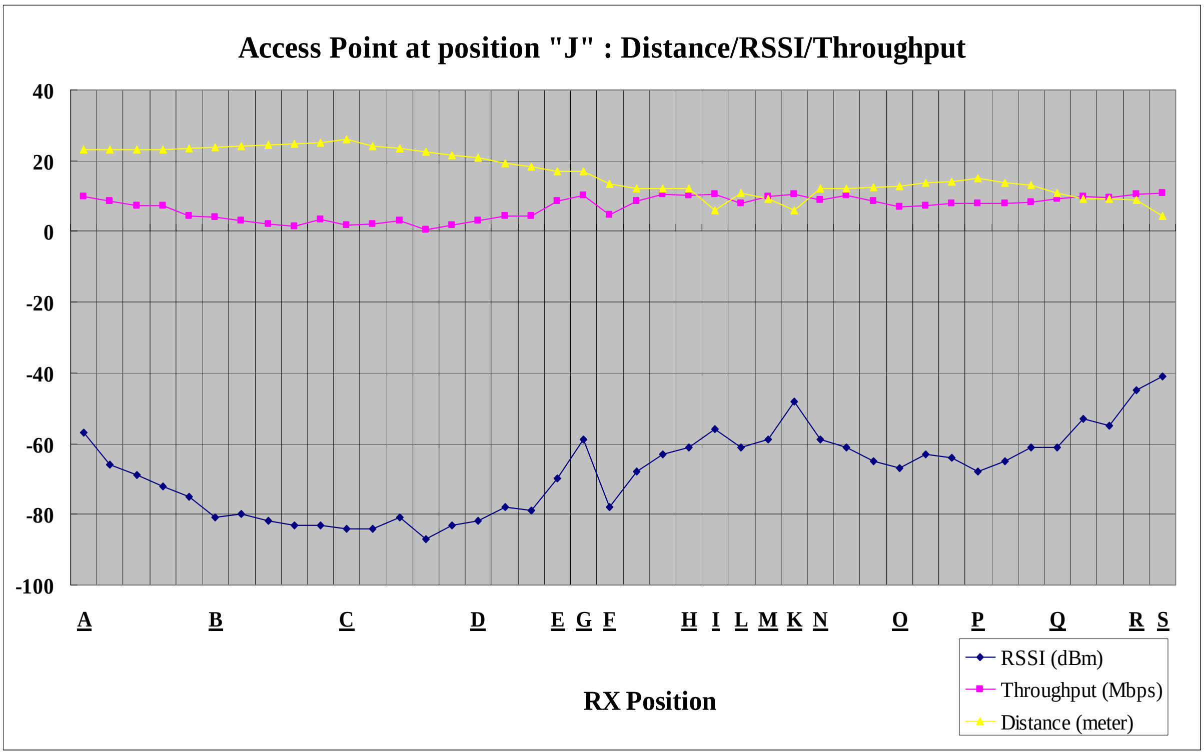


Figure 5.11: Distance/RSSI/Throughput for AP at position “J”.

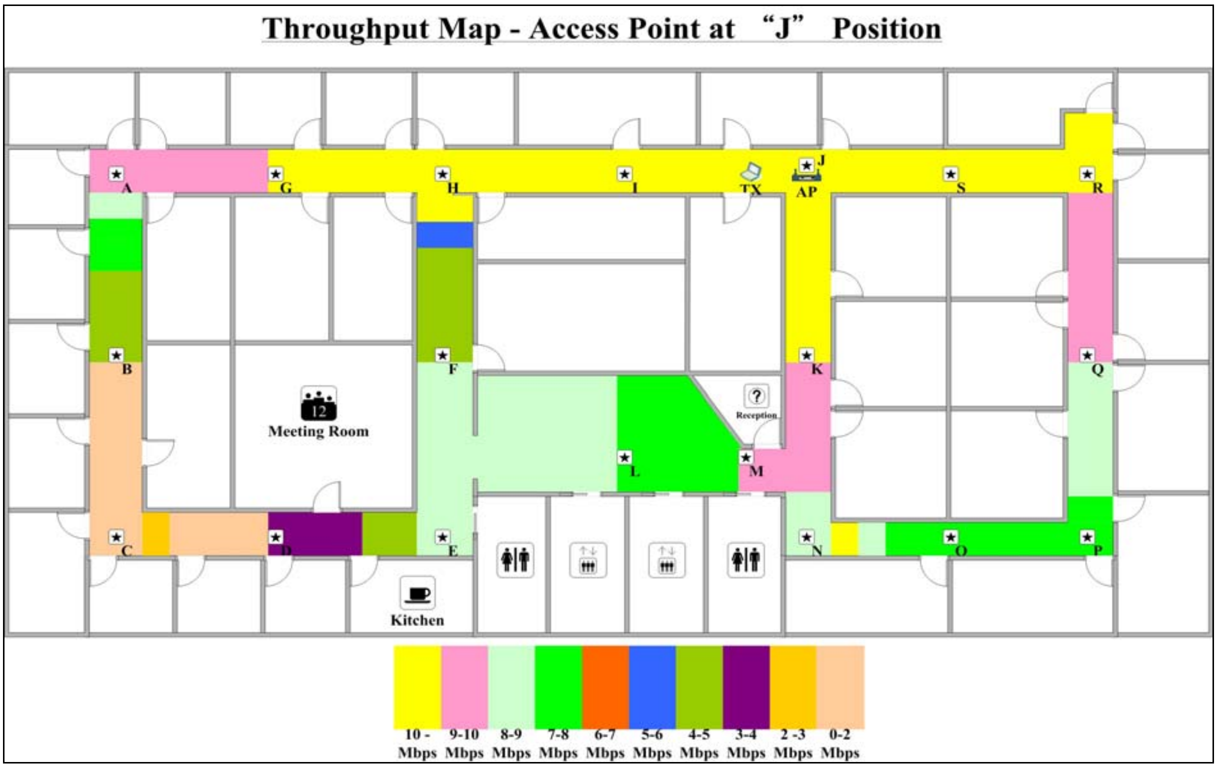


Figure 5.12: Throughput map for AP at position “J”.

## AP at Position “R”

Figure 5.13 shows the results of distance, RSS and throughput when the AP was located at position “R”. Even though RSS was same on different measurement points, throughput could be different. For example, measurement point “(H-3.5m)H-F” and “M” had the same RSS (-71 dBm, refer table B.5). Both measurement points were located in the NLOS from the AP. The throughput of measurement point “(H-3.5m)H-F” was 5.662 Mbps, which was lower than measurement point “M” (7.314 Mbps). However, the distance between “(H-3.5m)H-F” and the AP was 21.29 meters, while the distance between “M” and the AP was only 13.83 meters, thus distance is one of the key factors to determine WLAN throughput.

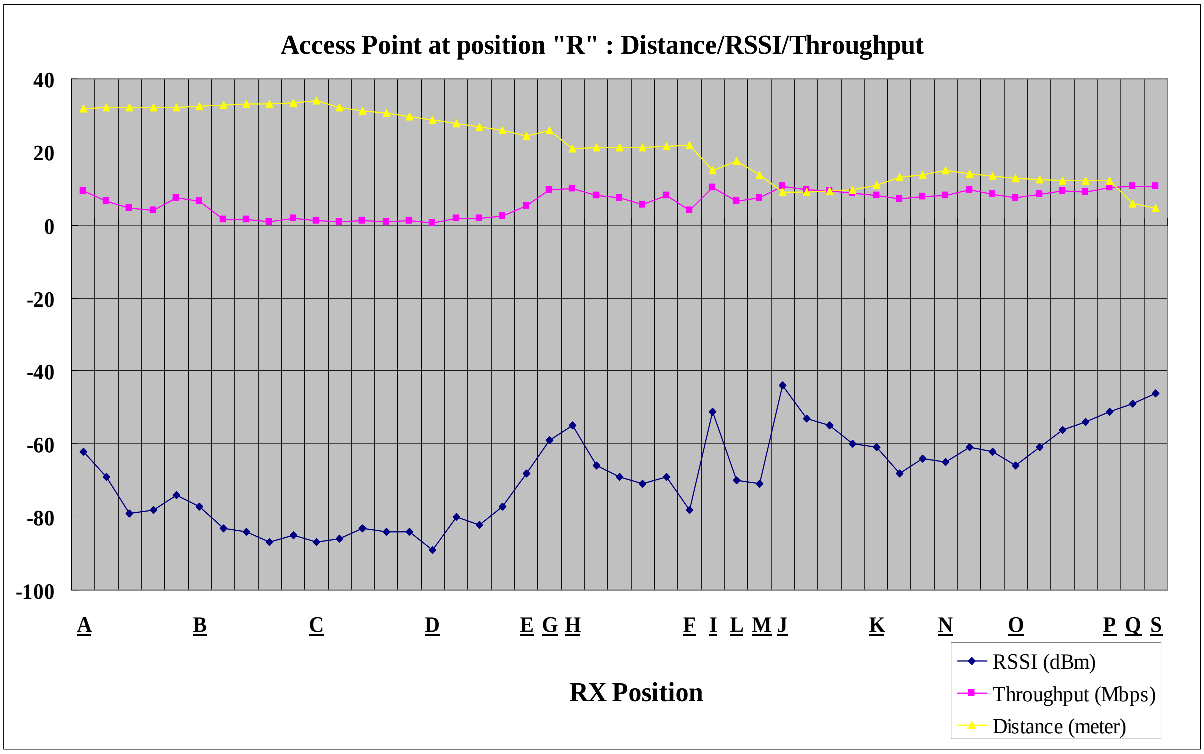


Figure 5.13: Distance/RSSI/Throughput for AP at position “R”.

Figure 5.14 shows throughput map of the AP when it was placed at position “R”. The average throughput was adequate on the “right-hand side” of the office. The area of insufficient throughput was on the “left-hand side” of the office. Overall, the throughputs were around 5~7 Mbps in the center of the office. The lower throughput area was large when AP was placed at position “R” rather than at position “J”. The results revealed that the AP at position “J” had better throughput than AP at position “R”.

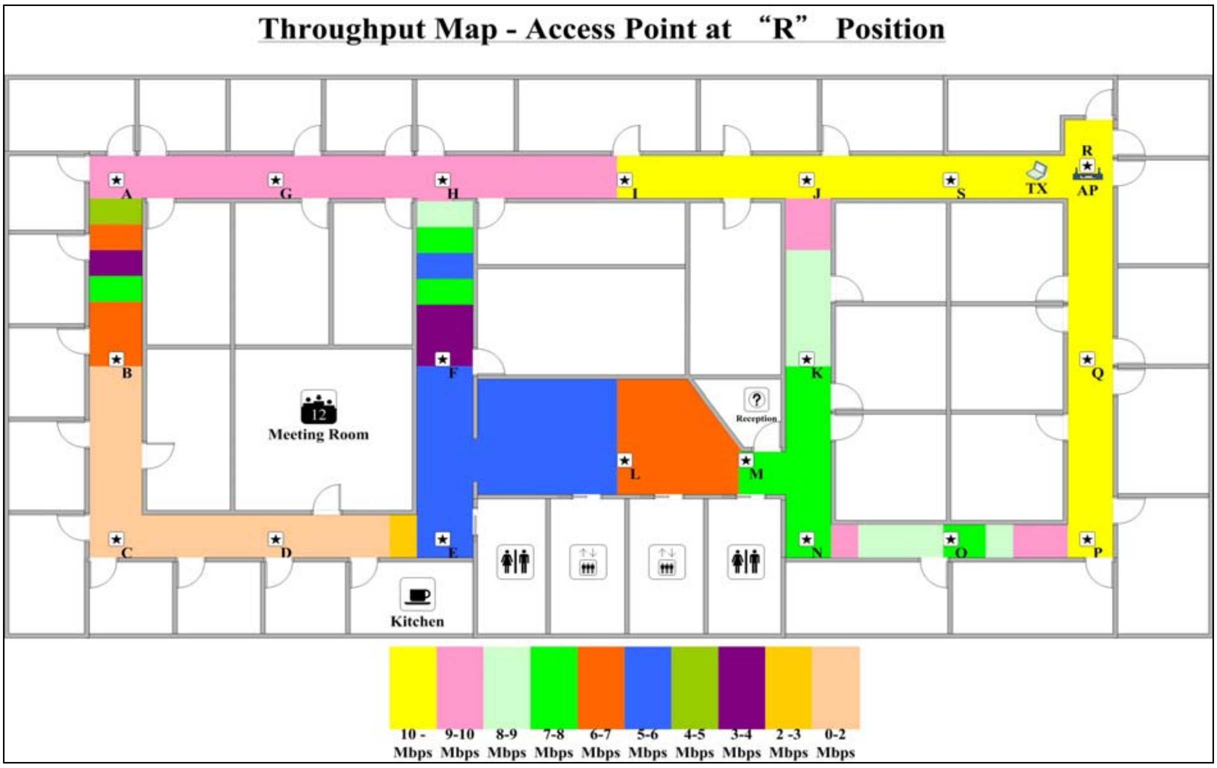


Figure 5.14: Throughput map for AP at position “R”.

## AP at Position “N-3M”

Figure 5.15 shows the results of distance, RSS and throughput when the AP was located at position “N-3M”. The average throughput was 10.085 Mbps (refer table C.10) on the “right-hand side” of the office. The average throughput was quite close to the estimated throughput (11 Mbps, refer table 5.1). Compared to other measurement results, the position “E-3M” is the best for AP placement to provide sufficient signal coverage and throughput to the “right-hand side” of the office.

The measurement results indicated that the throughput was decreasing along with low RSS and long distance. For example, in table B.6, the throughput was 9.973 Mbps (RSS: -51 dBm, distance: 6 meters) at measurement point “L”, the throughput of measurement point “E” was 7.836 Mbps (RSS: -60 dBm, distance 12.37 meters), and the throughput of measurement point “D” was 6.649 Mbps (RSS: -70 dBm, distance: 17.26 meters). In general, both RSS and distance are the key factors to determine throughput. Especially, throughput may vary significantly in harsh radio propagation environment.

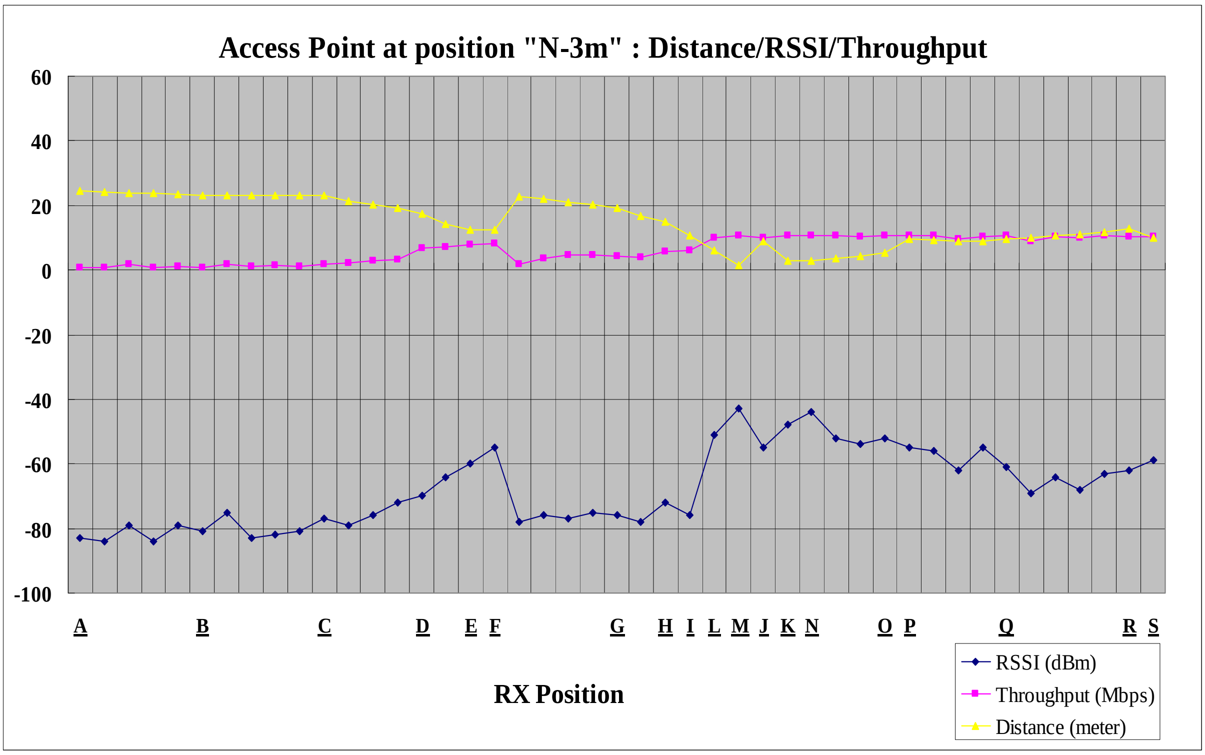


Figure 5.15: Distance/RSSI/Throughput for AP at position “N-3M”.

In figure 5.16, the throughputs were around 10 Mbps on the “right-hand side” of the office. However, large area between measurement points “A” and “C” did not have adequate throughput (less than 2 Mbps).

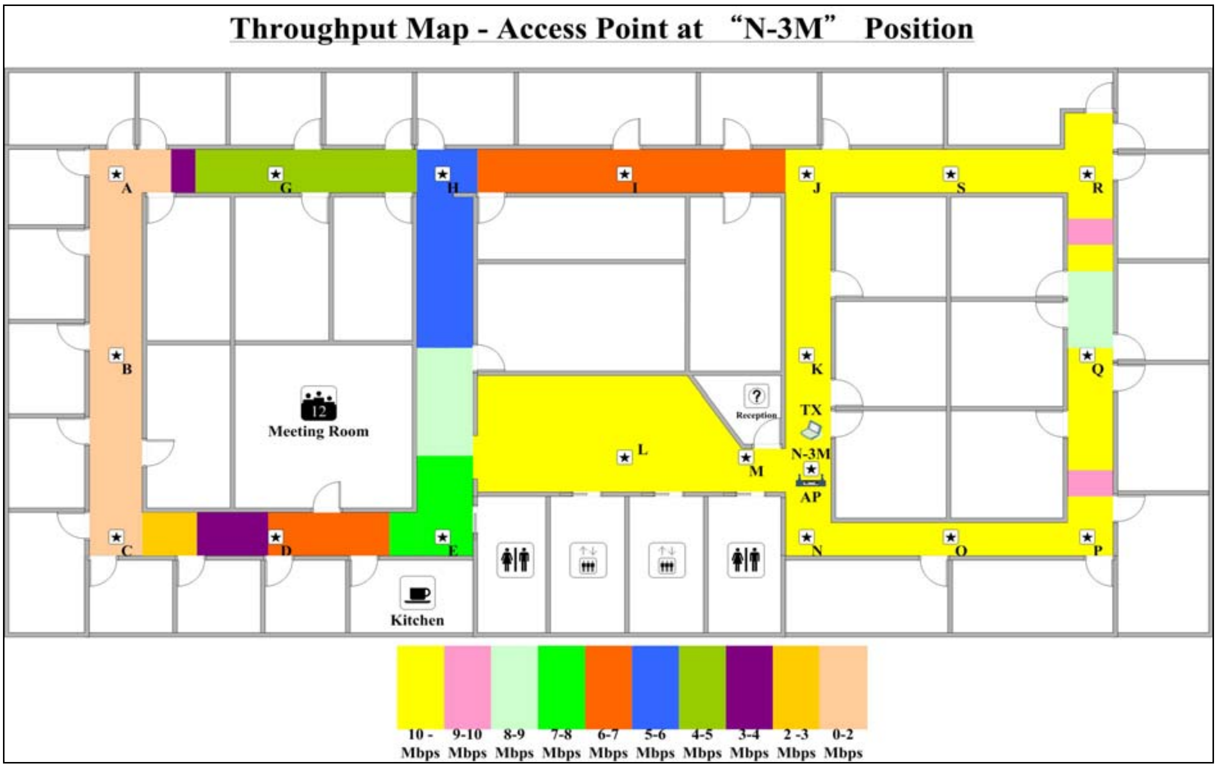


Figure 5.16: Throughput map for AP at position "N-3M".

According to our measurement results and discussion, RSS is one of the key factors to affect WLAN throughput. We also found that the performance of WLAN depends on many other factors, for instance, distance, AP position, the number of obstructions between a TX and a RX, radio propagation environment and LOS/NLOS conditions.

We have discussed the measurement results of an AP placement at measurement points "A", "G", "E-3M", "J", "R", and "N-3M". The signal strength and performance of the remaining AP placements ("I", "L", "H", "F" and "K") were lower than other positions. So we did not involve these measurement points in phase 2 measurements. The results of AP placements at positions "I", "L", "H", "F" and "K" are presented in appendix B.

### 5.2.2 Throughput Analysis

To conduct throughput analysis, we divided the measurement points into two groups: (1) right-hand side; (2) left-hand side (refer figure 4.1). The right-hand side contains measurement points “A”, “B”, “C”, “D”, “E”, “F”, “G” and “H”. Measurement points “J”, “K”, “M”, “N”, “O”, “P”, “Q”, “R” and “S” belong to the left-hand side. The measurement points “I” and “L” belong to both sides. We obtained eleven data suits from phase 1 measurements. We picked up three highest and lowest throughputs from both sides and calculate the average throughput.

| AP Position | Average Throughput (Mbps) (left-hand side) | Average Throughput (Mbps) (right-hand side) | Average Throughput (Mbps) (Both sides) |
|---|---|---|---|
| **A** | 8.838 | 3.857 | 6.384 |
| **G** | 8.554 | 5.006 | 6.78 |
| **H** | 6.935 | 4.845 | 5.89 |
| **F** | 6.964 | 4.273 | 5.619 |
| **E-3M** | 8.949 | 5.617 | 7.283 |
| **I** | 7.043 | 6.631 | 6.837 |
| **L** | 6.972 | 6.823 | 6.898 |
| **J** | 5.767 | 8.972 | 7.369 |
| **K** | 4.072 | 7.239 | 5.655 |
| **N-3M** | 4.776 | 10.085 | 7.43 |
| **R** | 5.305 | 8.82 | 7.062 |

Table 5.2: Average throughput of AP with different positions.

Table 5.2 shows the average throughput of an AP when it was located at different positions. When the AP was located at positions “A”, “G” and “E-3M”, it provided better average throughputs (8.838, 8.554, 8.949 Mbps) for the “left-hand side” of the office, while positions “J”, “R” and “N-3M” provided better average throughputs (8.972, 8.82, 10.085 Mbps) for the “right-hand side” of the office block.

The positions “I” and “L” had well balance throughputs for both sides, but the average throughputs (6.837 and 6.898 Mbps) were inadequate for both sides. Compared to the estimated throughput (11Mbps) of the IEEE 802.11g, the AP that was placed at positions “I” and “L” did not offer adequate throughput.

In conclusion, the measurement results revealed that multiple APs could provide better signal coverage and throughput than a single AP in this office. The positions “A”, “G”, “E-3M”, “J”, “R” and “N-3M” were potential locations for AP placement in multiple AP scenarios. The detailed results of throughput analysis are presented in appendix C.

### 5.2.3 Comments

From extensive measurements and discussion, some important conclusions have been drawn. Firstly, the impact of RSS on Wi-Fi link throughput is validated. The measurement results revealed that sufficient RSS does not guarantee sufficient throughput. WLAN throughput also depends on distance, the location of the AP, the number of constructions between the AP and the RX.

A single AP could cover the entire office, but throughput was insufficient in many locations. Furthermore, with changing AP positions, RSS and throughput were varying at the same time. When the AP was located at positions “A”, “G” and “E-3M”, signal coverage and throughput were acceptable on the “left-hand side” of the office. However, RSS and throughput were inadequate on the “right-hand side” of the office.

When the AP was located at positions “J”, “R” and “N-3M”, the results was opposite. The measurement results revealed that the location of AP would have a significant impact on RSS and throughput.

Results also shows that the measurement points of “A”, “G”, “E-3M”, “J”, “R” and “N-3M” are appropriate positions for phase 2 measurements. In phase 2 measurements, we configured and placed two APs in the different positions which we derived from phase 1 measurements.

The phase 2 measurement is discussed next.

## 5.3 Phase 2 Measurement

The phase 2 measurement aims to investigate the throughput between two APs. Two basic service sets (BSSs) were configured. Each BSS included an AP and a wireless station. One of the BSSs covered the “right-hand side” and the other one covered the “left-hand side” of the office. In configuring two BSSs, performance between two BSSs becomes a key factor to influence the end-to-end throughput, especially when two wireless stations are located at different BSSs, trying to communicate with each other. The numerical results are shown in table 5.3.

| Access Point Configuration | Distance (Meter) | Throughput (Mbps) | LOS/NLOS |
|---|---|---|---|
| **A-R: WDS with AP Mode** | 32 | 3.235 | LOS |
| **A-J: WDS with AP Mode** | 21 | 3.663 | LOS |
| **G-R: WDS with AP Mode** | 26 | 5.281 | LOS |
| **G-J: WDS with AP Mode** | 17 | 4.271 | LOS |
| **E-3m-N-3M: WDS with AP** | 12 | 5.61 | LOS |
| **E-3m-N-3M: AP with Ethernet Connection** | 12 | 14.834 | LOS |

Table 5.3: Comparison with different AP configurations and placements.

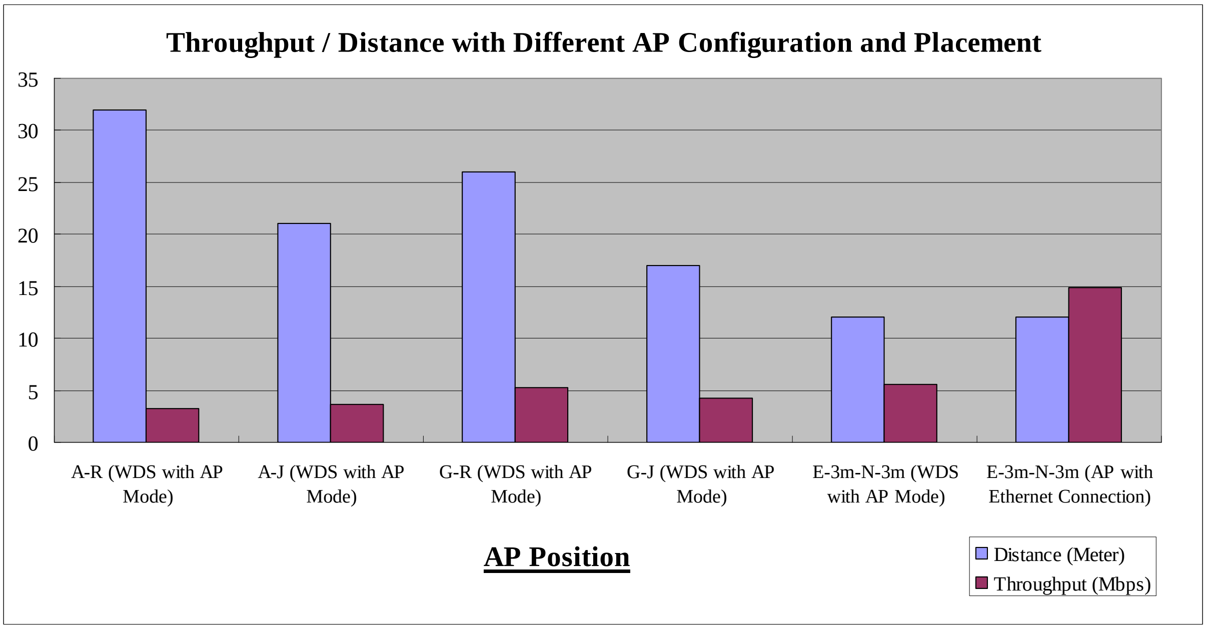


Figure 5.17: Comparison with different AP configurations and placements.

Figure 5.17 shows the throughput with different AP configurations and placements. When the APs were configured as “WDS with AP” mode and placed at position “E-3M” and “N-3M”, throughput was better than the other positions. This is because the distance between positions “E-3M” and “N-3M” is shorter than the other positions. Also, the radio propagation environment of “E-3M” and “N-3M” was less harsh than other positions.

We verified the impact of distance on WLAN performance again. The results show that the distance between two APs had a slight impact on AP-to-AP throughput in LOS condition. In table 5.3, the throughput decreased with an increased in the distance between two APs, except for APs at positions “G and “R”. Thus, the measurement results revealed that the location of APs, and radio propagation environment would be the major factors to influence throughput rather than the distance in LOS condition.

The throughput of “WDS with AP mode” (5.61 Mbps) was only half of the estimated throughput of a signal AP (11 Mbps). This is due to the fact that the APs need to deal with traffic between wireless stations and to exchange data with other APs in the “WDS with AP mode”.

On the other hand, when two APs were configured as “AP mode” and a Cat-5 Ethernet cable was used to link two BSSs, throughput increased to 164% (from 5.61 Mbps to 14.834 Mbps). The “AP mode” with Ethernet connection used a Cat-5 cable to link two BSSs. The traffic between BSSs was served by Ethernet (100 Mbps). There was only one hop between the AP to the wireless nodes on both BSSs. Thus, throughput of “AP mode” with the Ethernet connection was much better than the “WDS with AP mode”.

The optimal positions (E-3M and N-3M) for two APs placement were obtained from phase 2 measurements. The position “E-3M” and “N-3M” were the candidate measurement points for the third phase measurements.

The results of phase 3 measurement are presented next.

## 5.4 Phase 3 Measurement

The APs were configured as “WDS with AP mode” in scenario 10 and “AP mode” with Ethernet connection in scenario 11. Both APs were placed at position “E-3M” and “N-3M”. Two laptops were connected to different APs. TX was placed at a fixed position and RX was moved around to different measurement points in the office. The results of “WDS with AP mode” and the results of “AP mode” with Ethernet connection are presented in section 5.4.1 and 5.4.2 respectively.

### 5.4.1 WDS with AP Mode

The results of RSS and throughput under "WDS with AP mode" are shown in figure 5.18 and 5.19. The numerical results are presented in appendix D (tables D.1 and D.2).

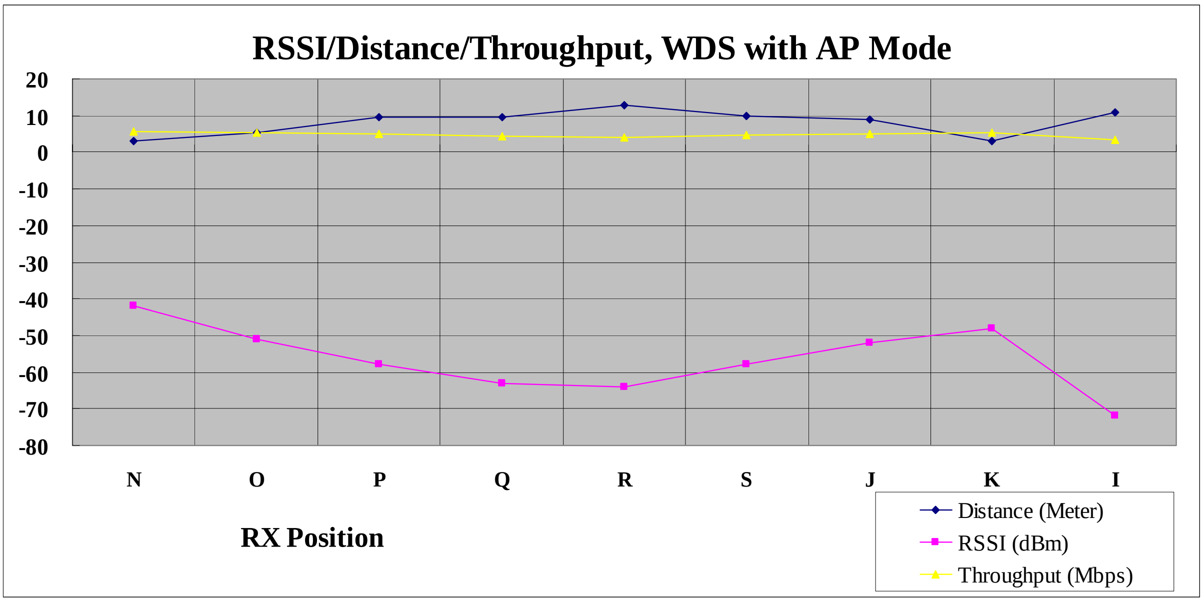


Figure 5.18: Results for WDS with AP mode TX at BSS1.

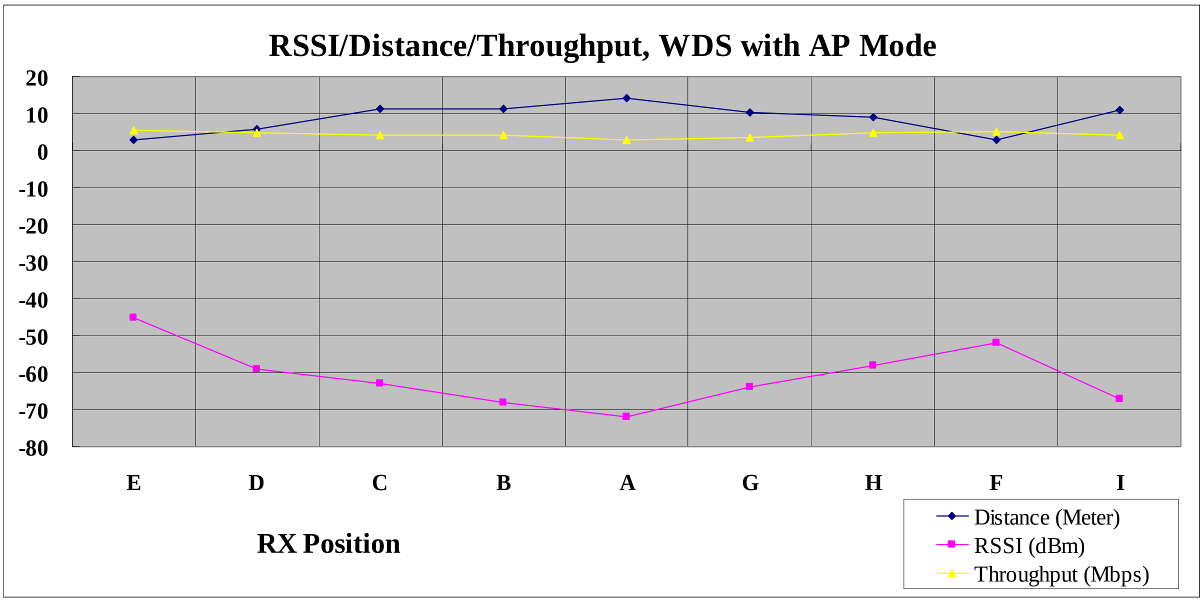


Figure 5.19: Results for WDS with AP mode TX at BSS2.

The RSS of “WDS with AP mode” was close to phase 1 measurement results because the radio propagation environment did not change significantly. The average throughput (4.736 and 4.364 Mbps, refer tables D.1 and D.2) were lower than the preliminary measurement results (5.755 Mbps, refer table A.3) and phase 2 measurement results (5.61 Mbps, refer table 5.3). The reason of varying throughput results is that the RX position was changed during phase 3 measurements. Furthermore, when RX was located close to the AP, it had better throughput and RSS, for example, measurement points “N”: -42 dBm / 5.562 Mbps, and “E”: -45 dBm / 5.332 Mbps.

The measurement results showed that RSS and location of AP placement have influenced throughput and performance. For example, when RX was located at position “I” and was associated with the AP (SSID: Wellington), the throughput was only 3.241 Mbps with -72 dBm RSS (refer table D.1). When RX was located at position “I” and was associated with the AP (SSID: Auckland), we gained a throughput of 4.237 Mbps with -67 dBm RSS (refer table D.2). Therefore, the results revealed that radio propagation environment and lower RSS would cause lower throughput and the position of AP had impact on both the throughput and RSS.

When RX was located at position “I” and was associated with different APs, we obtained different RSSs (-72 and -67 dBm). When receiver sensitivity of WLAN adapter is -74 and -69 dBm, the data rates are 36 and 48 Mbps (refer table 5.1). Thus, the estimated throughputs are 7.2 and 9.6 Mbps (refer table 5.1). Since we configured the APs as “WDS with AP mode”, the throughputs were only half of normal “AP mode” throughput. The estimated throughputs of position “I” should be 3.6 and 4.8 Mbps. The measurement results (3.241 and 4.237 Mbps) were close to the estimated throughput.

### 5.4.2 AP Mode With Ethernet Connection

Figure 5.20 shows the results of distance, RSS and throughput when TX was located at 2 meters from the AP (SSID: Auckland). Figure 5.21 shows results of distance, RSS and throughput, when TX was located at 2 meters from the AP (SSID: Wellington).

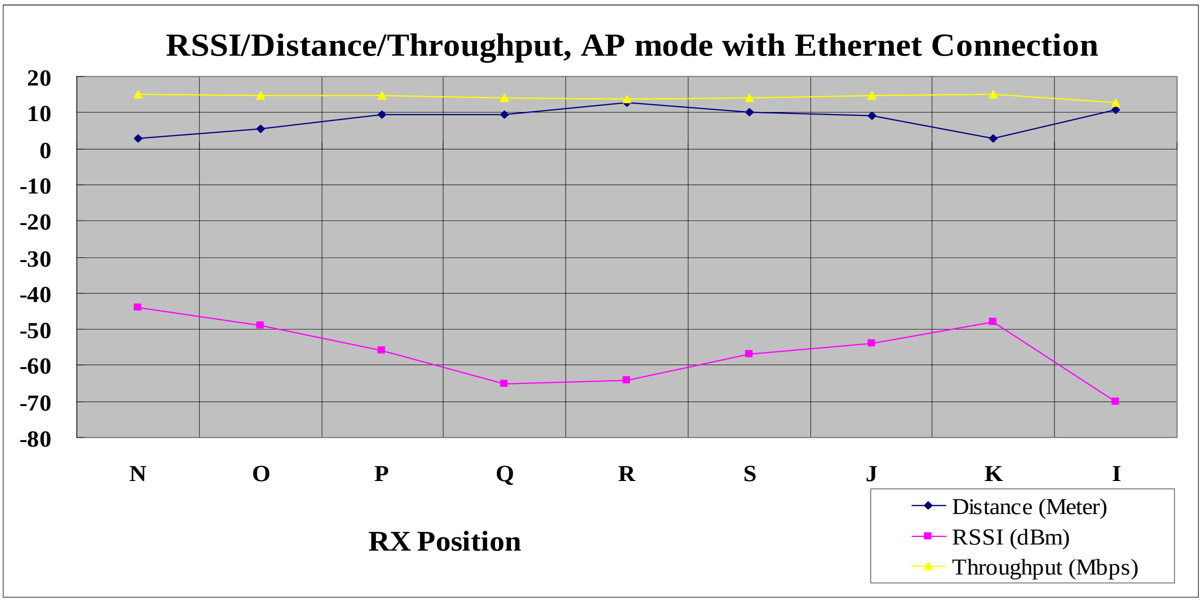


Figure 5.20: Results for AP mode with Ethernet connection TX at BSS1.

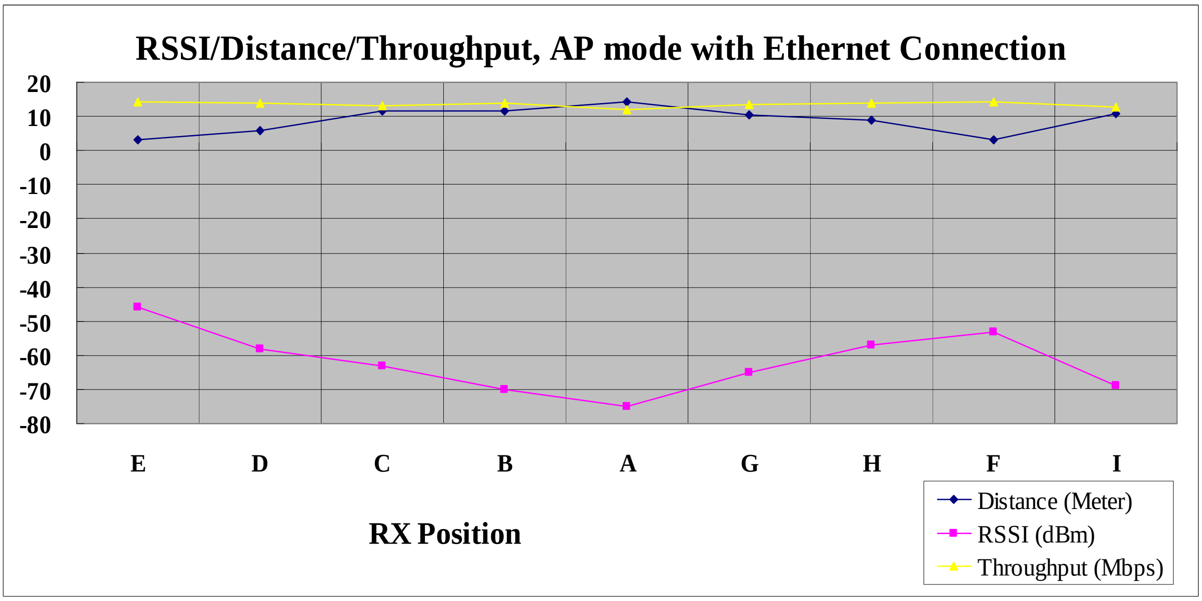


Figure 5.21: Results for AP mode with Ethernet connection TX at BSS2.

The average throughput of the “AP mode” with Ethernet connection was 14.347 and 13.749 Mbps (refer tables D.3 and D.4). These results were close to phase 2 measurement results (14.834 Mbps, refer table 5.3).

Furthermore, under same AP configuration, RSS was -43 dBm in the preliminary measurement (refer table A.4), which was much better than phase 3 measurement results (-44 dBm ~ -70 dBm). However, the throughput of preliminary measurement (11.863 Mbps, refer table A.4) was 18% lower than this measurement (14.347 Mbps). This is due to the fact that different locations of APs and RX, and radio propagation environment lead to inconsistent results. Thus, the results revealed that positions of APs and RX, and radio propagation environment have important impact on Wi-Fi link throughput.

### 5.4.3 Comments

An exhaustive propagation study and phase 3 measurement results are presented. The results showed that two APs can provide much better signal strength and throughput than a single AP in this office. With two APs configuration, throughput can be quite close to the estimated throughput. Thus, two APs are found to be sufficient for this entire floor coverage.

With the same radio propagation environment and similar RSS value, the average throughput of “WDS with AP mode” was much lower than “AP mode” with Ethernet connection. Therefore, “AP mode” with Ethernet connection configuration provides better performance than the “WDS with AP mode” configuration.

In conclusion, according to our measurement results, we propose two solutions for AP placement in the office block under study. The first solution is to use the “WDS with AP mode” under less traffic condition between two APs. The performance of “WDS with AP mode” is only around a third of “AP mode” with Ethernet connection, but it has the advantage of cable free deployment. On the other hand, the “AP mode” with Ethernet connection is recommended for high traffic condition between two APs.

## 5.5 Capacity Estimation of WLAN

The throughput of both a single AP and multiple APs, and AP configurations are discussed in sections 5.1 to 5.4. Capacity estimation is an important procedure during WLAN design. The capacity of an AP not only depends on throughputs, but also the type of application.

Table 5.4 illustrates average data size and common application types including distributed computing, web transaction, database entries, payroll entries and teleconference. All of above application types are quite popular, especially web transactions. Therefore, the capacity analysis focuses on web transaction.

| **Application** | **Average Completion Time (Seconds)** | **Average Data Size (Bytes)** |
|---|---|---|
| Distributed Computing (Batch Mode) | 1000 | 100,000,000 |
| Web Transactions | 10 | 10,000 |
| Database Entries/Queries | 2–5 | 1,000 |
| Payroll Entries | 10 | 100 |
| Teleconference | 100 | 100,000 |

Table 5.4: Completion times and data sizes for applications [96].

The average data size of web transaction application (80Kb) seems too small for graphic-rich web sites. We assume that an appropriate data size is 256 Kb, which is based on minimum downstream speed of Xtra wireless plan [97].

Capacity is the number of concurrent users who can access application through an AP. Each web transaction consumes 256 Kbps bandwidth. The capacity is calculated below:

***Capacity*** *(number of concurrent users) = (Throughput Mbps ) / (256Kbps)*

Table 5.5 shows the capacity of an AP at different positions. For example, when AP is located at position "E-3M" and "N-3M", it can offer 28 and 29 users to access web application concurrently.

| **AP Position** | **Average Throughput (Mbps)** | **Capacity (number of concurrent users)** |
|---|---|---|
| A | 6.348 | 25 |
| G | 6.780 | 26 |
| H | 5.890 | 23 |
| F | 5.619 | 22 |
| E-3M | 7.283 | 28 |
| I | 6.837 | 27 |
| L | 6.898 | 27 |
| J | 7.369 | 29 |
| K | 5.655 | 22 |
| N-3M | 7.430 | 29 |
| R | 7.062 | 28 |

Table 5.5: WLAN capacity with a signal AP for web application.

Table 5.6 shows the capacity of two APs scenario. For instance, when two APs were located at "E-3M" and "N-3M", in our case study the total 57 users can access graphic-rich web sites concurrently. However, the number of permanent staff was around 18 on the "right-hand side" and 17 on the "left-hand side" of the office. Although the estimated capacity was more than the number of current staff, the rest of the capacity can be used for visitors.

| AP Position BSS 1 | Throughput (Mbps) | Capacity (A) | AP Position BSS 2 | Throughput (Mbps) | Capacity (B) | Total Capacity (A+B) |
|---|---|---|---|---|---|---|
| **A** | 8.838 | 25 | **R** | 8.820 | 28 | 53 |
| **A** | 8.838 | 25 | **J** | 8.972 | 29 | 54 |
| **G** | 8.554 | 26 | **R** | 8.820 | 28 | 54 |
| **G** | 8.554 | 26 | **J** | 8.972 | 29 | 55 |
| **E-3M** | 8.949 | 28 | **N-3M** | 10.085 | 29 | 57 |

Table 5.6: WLAN capacity with two APs for web application

In conclusion, the throughput, RSS, and capacity plan revealed that two APs not only provide sufficient RSS and throughput, but also sufficient capacity to support staff who worked in the office.

## 5.6 Recommendations for Access Point Deployment

To find optimal location of AP placement, we conducted an extensive series of propagation measurements and an in-depth comparison of throughput with different AP placement scenarios and AP configurations. We also assessed the capability of APs. However, all of those only solved partial issues of AP deployment. Therefore, we would like to provide some recommendations for practical AP deployment which we derived from this study. The recommendations are presented based on two scenarios: a small office, a home office (SOHO) environment (section 5.6.1) and a medium-sized business environment (section 5.6.2).

### 5.6.1 SOHO Environment

Due to the availability of low cost APs, the deployment of WLAN is increasing at home and small office. Figure 5.22 shows AP deployment scenario in a SOHO environment. We assume that a single AP would be sufficient for SOHO environment.

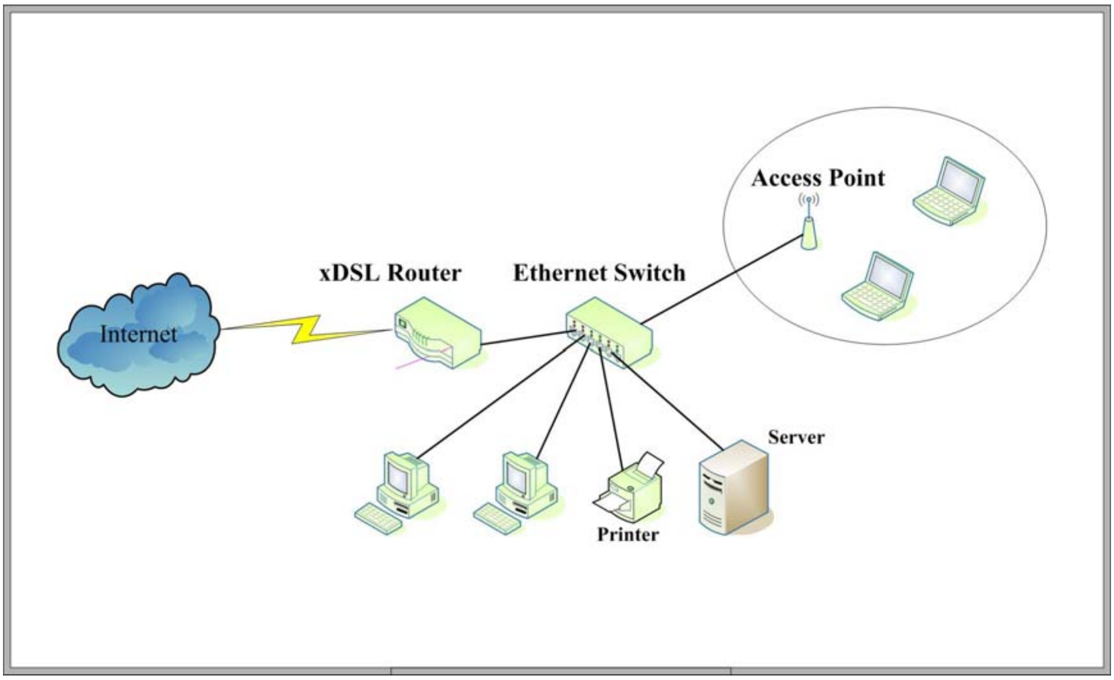


Figure 5.22: Small office and home office scenario.

Although SOHO WLAN deployment is simple, WLAN design should take into account the following points.

- Site survey: the site survey could help WLAN designers to estimate radio signal coverage and the number of APs in rough, search the possible interference sources, and understand geography of real environment [94].
- Interference: AP should be as far as possible away from other radio equipment (e.g. microwave oven, cordless phone) due to avoiding interference.
- RSS: users should not rely on RSS only. Our study results showed that distance, obstructions and LOS/LOS also affect the WLAN performance.
- Radio channel assignment: with popular deployment of AP, careful channel

assignment could avoid co-channel interference. We suggest that regular channel scanning is useful for channel utilization. If a channel is used by other APs, it is necessary to re-assign a channel number. When the area is quite crowded with multiple APs, selecting less interference channel would give better performance.

- Trade-offs between performance and network security: although enabling security mechanism could give extra overhead in WLAN performance, it is necessary to set up a security mechanism. However, if the security setting results in a lower performance, additional APs would be an alternative to solve performance issue rather than not having a security mechanism in place.

### 5.6.2 Medium-sized Business Environment

Figure 5.23 shows AP deployment scenario in a medium business environment. Some recommendations have been discussed in section 5.6.1 However, multiple APs deployment is complex and challenging, specially in a crowded office and multiple buildings environment.

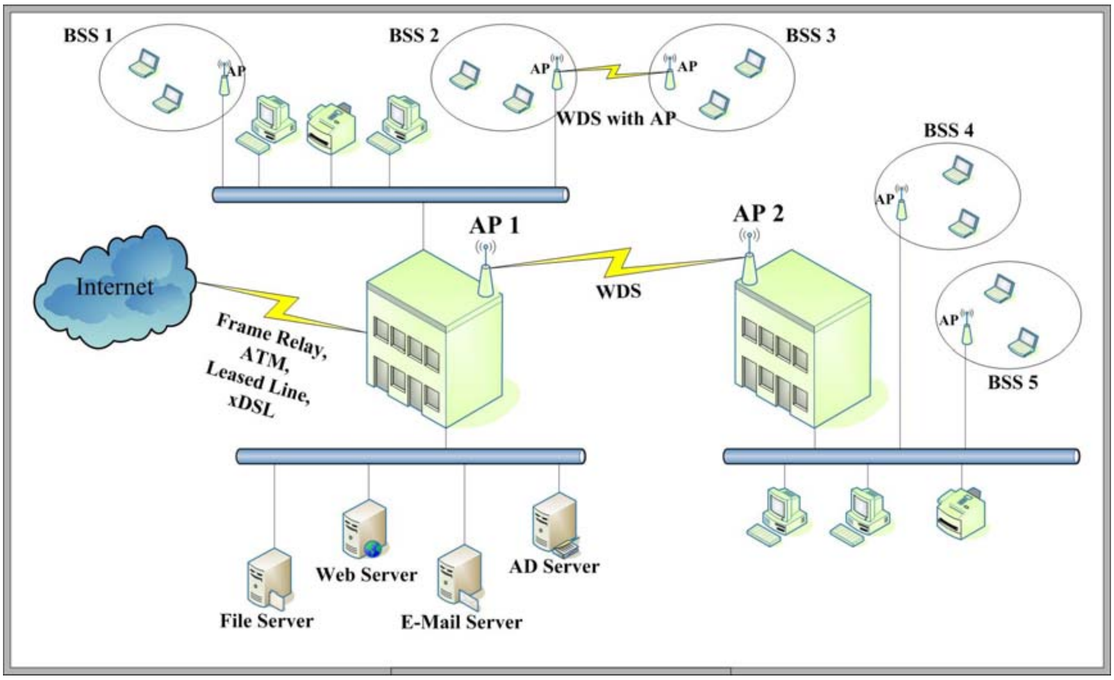


Figure 5.23: Medium-sized business scenario.

The following notes are needed to be considered for the deployment.

- Multiple APs placement: 15% radio signal overlap between APs would provide adequate signal strength for seamless roaming service[94].
- Channel assignment is related to WLAN performance in adjacent BSSs. Radio signal should be overlapping to provide seamless roaming service. It could cause co-channel interference without appropriate channel assignment.
- WDS with AP mode: our measurement study indicated that maximum AP performance is only half of AP mode when APs were configured as WDS with AP mode in a direct LOS. Thus, APs placement and capacity plan are extremely important in WDS with AP mode.
- WDS mode: figure 5.23 shows that AP1 and AP2 are linked via “WDS mode”. “WDS mode” can provide point-to-point wireless connection between two buildings. As long as transmission power of APs is fair enough between two buildings, “WDS mode” would be an appropriate solution.

  Although performance WDS mode cannot compete with Fast Ethernet and Gigabit Ethernet, WDS mode can be an alternative as backup line between two buildings. Furthermore, omni-directional antenna is normally used with AP inside a building. Higher gain, outdoor directional antenna (e.g. Yagi antenna) would increase performance of radio signal in transmitting and receiving and reduce interference from unwanted sources in the outdoor environment.
- Physical security: AP might be placed in the open area due to convenient access and performance consideration. To avoid APs to suffer from physical attack is an important issue in WLAN design and deployment. Performance and physical security would be in a dilemma. Careful assessment of risk and feasibility would be helpful to minimize the potential risk.

## 5.7 Summary

The ad-hoc mode has the advantage in forming a WLAN quickly without AP involved. However, the preliminary measurement results showed that ad-hoc mode is inappropriate in the crowded office environment due to insufficient signal coverage. Unlike the ad-hoc mode, the infrastructure mode uses APs to repeat and boost signals.

Phase 1 results showed that RSS has a significant impact on WLAN throughput. The throughput was changing with varying RSS. However, the throughput was not only affected by signal strength, but also distance, obstructions, and radio propagation environment. Furthermore, a single AP would have sufficient signal coverage in this office; however, the signal strength and throughput would be inadequate in some locations of the office.

The positions “I” and “L” could have better throughput coverage for both the “right-hand side” and the “left-hand side” of the office than other positions. However, the average throughput at positions “I” and “L” was lower than the estimated throughput. On the other hand, the positions “A”, “G” and “E-3M” would have better throughput and signal coverage on the “left-hand side” of the office. The positions “J”, “R” and “N-3M” would provide adequate signal strength and throughput on the “right-hand side” of the office. Phase 1 results gave us an implication for using an additional AP to provide sufficient throughput and signal strength in the office.

Phase 2 results showed that end-to-end throughput was affected by position of APs and configuration of APs. The results showed that inter-AP throughput was much better when APs were placed at positions “E-3M” and “N-3M”.

Phase 3 results showed that using Ethernet as distribution system would have much better end-to-end performance than using wireless distribution system in multiple hops WLAN environment. The “WDS with AP mode” has the advantage of having multiple functions in AP deployment and being cable free. However, the throughput between BSSs may be inadequate under high traffic condition.

Capacity estimation is an important part of network design. The number of concurrent users and characteristics of application would have significant influence on network capacity. An accurate estimation of WLAN capacity not only save cost, but also efficiency of spatial utilization and sufficient performance.

Site survey is the first step in WLAN design. Performing site survey would collect important information in terms of real radio propagation environment (for example, sources of potential interference, possible locations of AP). Moreover, a single AP deployment is simpler than the deployment of multiple APs. During AP deployment, in addition to maintaining the distance from the sources of interference, channel assignment and security mechanism are important issues in terms of WLAN performance. Although different AP configurations would provide higher flexibility of WLAN design, an appropriate AP configuration would ensure sufficient performance.

# Chapter 6

# Implications and Future Research

In chapter 5, we have discussed the propagation measurement results and recommendations for AP deployment. This chapter discusses research implications and possible directions for future research.

## 6.1 Implications

By conducting various preliminary experiments, we developed a better understanding of the characteristics of AP and its maximum throughput, the RSS of wireless adapter, and configurations of AP and WLAN adapter, which are important prior to conducting propagation measurements and AP deployment. The preliminary measurements not only provide important data used as reference, but also help us to understand AP configuration and the practical AP deployment. The characteristics of AP or wireless adapter would vary with different models and vendors. The different WLAN equipment may lead to inconsistent results, hence using the same equipment is important for measurement and deployment.

Real and accurate results for AP placement can be arrived at by extensive propagation measurements. However, an extensive propagation measurement is time consuming and labor extensive. Our measurement results would provide significant implications and efficiencies in selecting proper positions for AP placement in similar propagation environment. Furthermore, many AP placement plans are only based on RSS. Our measurement results indicate that RSS was not precise enough to present real performance of WLANs. Therefore, an extensive experimental study is initially required to derive more accurate results before any practical AP deployment.

Phase 2 measurement results indicated that location of APs had significant impact on the end-to-end throughput in the multiple-hops WLAN environment. Throughputs are subject to change when multiple APs are placed at different locations.

Phase 3 measurements indicated that the performance of “WDS with AP mode” was much lower than the wired distribution system. Although the “WDS with AP mode” is a flexible solution to WLAN deployment, it is important to assess the traffic between two networks before implementing the “WDS with AP mode”.

## 6.2 Future Research

We only investigated the throughput of “WDS mode” in the meeting room. However, the “WDS mode” has an advantage in providing wireless point-to-point communication in outdoor environment. Thus, it may be appropriate to investigate the impacts of signal strength on outdoor wireless mesh networks for future research.

Multimedia applications and voice over IP technology have been widely deployed in wired networks. Recently, with higher demand on mobility, WLANs provide an alternative mobile platform to telecommunication and multimedia applications. However, the original IEEE 802.11 standard did not support real-time application. Although the task group E of IEEE 802.11 committee developed the IEEE 802.11e to enhance 802.11 MAC layer for supporting QoS, the final version of 802.11e standard was issued in November, 2005. Therefore, many current deployed APs do not support QoS function. An investigation into the impact of WLAN performance on real-time applications can be conducted by experimental measurement. The study would help WLAN designers to re-assess current AP capability to support real-time applications.

Due to the characteristics of radio wave, WLAN provides an open channel for all people to access networks, especially hacker. Future research can focus on the investigation of the impact of security mechanisms on Wi-Fi throughput. It would provide a significant insight into selecting security mechanism for WLAN design and deployment.

In this research, propagation measurement approach has been used to investigate WLAN performance. For generalization of research findings, a simulation approach is suggested for future work.

# Chapter 7

# Summary and Conclusions

We investigated the impact of signal strength on Wi-Fi link throughput through a series of propagation measurements. Because of the low cost wireless cards and APs, WLANs have been widely used in the office, home and Internet hotspots to provide convenient network services. The challenges in WLAN implementation is different from wired LAN due to the dynamic and unpredictable nature of radio signal propagation. The AP placement has a strong impact on both RSS and throughput. This study investigates the relationship of RSS and throughput by conducting various AP placement scenarios. In addition, WLANs capacity plan and some recommendations for AP deployment were discussed.

Chapter 2 reviewed IEEE 802.11 standard, radio propagation measurement and signal strength. A good understanding of IEEE 802.11 is required for WLAN design, deployment and troubleshooting. Furthermore, the IEEE 802.11b and 802.11g are the mainstream standards for WLANs. On the other hand, the emerging standard (802.11n) is in the final stage of its development. The IEEE 802.11n standard has significant enhancement on PHY and MAC efficiency.

We obtained valuable data in terms of conducting measurement study in the area of WLAN from previous researchers' experiences. Especially, it is important to use the same equipment for measurements and deployment to avoid gaps between measurements and practical AP deployment.

Radio interference is a serious problem influencing WLAN performance due to heavy load of ISM band. Occasionally, it is difficult to avoid radio interference but maintaining an appropriate distance from the sources of interference is an important guideline for AP deployment.

Base station placement is related to signal coverage, spectral efficiency, performance and cost of WLAN deployment. In the multiple-hops WLAN, overlapping APs would provide adequate signal coverage for seamless roaming. If adjacent APs use an overlapping channel, it causes co-channel interference and degrades WLAN performance. Therefore, both signal coverage and appropriate channel assignment are the goals of base station placement.

A variety of transmission overheads would result in a large gap between the theoretical data rate and throughput. It seems that there is some misunderstanding about the data rate and throughput. Although the IEEE 802.11g has a higher data rate (54 Mbps) than the IEEE 802.11b (11 Mbps), the IEEE 802.11b has lower overheads (80% overhead for the IEEE 802.11g, while only 55% overhead for the IEEE 802.11b). A lack of understanding about data rate and throughput may cause inappropriate capacity planning.

Propagation measurement (as discussed in chapter 3) is the research methodology used in the study. To gain a realistic and accurate RSS and throughput of WLAN in the obstructed office environment, it is difficult to use either an analytical modeling or computer simulation. Thus, propagation measurement seems to be an appropriate methodology for optimal AP placement.

In chapter 4, we discussed the design and planning of propagation study. The equipment used in the experiments is shown in section 4.2 and appendix E. The measurement environment including layout and main partition material are described. The detailed AP and wireless adapter configuration and scenarios are discussed.

The measurement results are discussed in chapter 5. Our experimental measurements were divided into four phases. The preliminary measurement was done to understand the characteristics of WLAN equipment and the throughput of different AP configurations. The preliminary measurement results showed that ad-hoc mode cannot provide sufficient signal coverage in the office under consideration. It requires one or more APs to boost up the signal.

Extensive measurements were performed with an AP in phase 1. RSS and throughput were collected from different locations of AP placement. While a single AP could cover the entire office, throughput was unacceptable in many measurement points. We required an additional AP to offer sufficient throughput. Moreover, phase 2 measurement was carried out at two locations (“E-3M” and “N-3M”) that had better inter-APs throughput than other locations.

Phase 3 measurement showed that two APs could provide adequate RSS and throughput in the office. The configuration of “AP mode” with Ethernet connection would have much better inter-APs performance than the “WDS with AP mode”. However, the “WDS with AP mode” has the advantage of being cable free. Furthermore, two solutions for different requirements in WLAN design and deployment were discussed.

The number of users that an AP can serve concurrently is an important issue of WLAN design and AP placement. An understanding of the characteristics of application and network throughput would help to calculate capacity. The throughputs and RSS were gained from extensive measurements. The average data size was based on the bandwidth of the Xtra wireless plan. Our capacity plan showed that two APs would provide sufficient throughput to serve every staff in the office.

Previous studies on WLANs have focused more on improving the performance of PHY and MAC, transmission power control, and channel assignment than AP placement. According to our experience, observation and the propagation measurements conducted in this experimental study, we have concluded that an appropriate AP placement can improve WLAN performance significantly. Accordingly, we have proposed some recommendations for AP deployment through two WLAN deployment scenarios.

In chapter 6, we discussed some implications of this study and possible directions for future research. RSS is an important factor for AP placement. Many AP placement projects are only based on RSS; however, over reliance on RSS may lead to wrong AP deployment.

Many WLANs are deployed in indoor environments. In fact, the ‘WDS mode” supports point-to-point data communication. It is an appropriate solution to deploy WLAN in adjacent buildings. The future research may investigate WLAN performance issues in outdoor mesh networks.

Comparison of measurement results by simulation is suggested as future research. Furthermore, wireless security is a momentous issue in WLANs. Various security mechanisms have been developed and implemented in APs and wireless nodes. An investigation on the impact of security mechanisms on WLAN performance is also suggested as future research.

# References


[1] F. Ye, H. Yang, and B. Sikdar, "Enhancing MAC Coordination to Boost Spatial Reuse in IEEE 802.11 Ad Hoc Networks," presented at IEEE International Conference on Communications, 2006, pp. 3814-3819.

[2] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "Performance analysis of IEEE 802.11 DCF in presence of transmission errors," presented at IEEE International Conference on Communication, 2004, pp. 3854-3858.

[3] L. Zhang, Y. Shu, and W. W. Yang, "Performance Improvement for 802.11 Based Wireless Local Area Networks," presented at IEEE International Conference on Communications, 2006, pp. 4774-4779.

[4] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "Optimisation of RTS/CTS handshake in IEEE 802.11 wireless LANs for maximum performance," presented at IEEE Global Telecommunications Conference Workshops, 2004, pp. 270-275.

[5] K. Xu, M. Gerla, and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks," presented at IEEE Global Telecommunications Conference, 2002, pp. 72-76.

[6] J. Rao and S. Biswas, "Transmission power control for 802.11: a carrier-sense based NAV extension approach," presented at IEEE Global Telecommunications Conference, 2005, pp. 3439-3444.

[7] S. Datta and S. Biswas, "Energy savings by intelligent interface idling in 802.11 based wireless networks," presented at IEEE International Conference on Electro Information Technology, 2005, pp. 6-12.

[8] A. Muqattash and M. M. Krunz, "A distributed transmission power control protocol for mobile ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 3, no. 2, pp. 113-128, 2004.

[9] J. K. L. Wong, A. J. Mason, M. J. Neve, and K. W. Sowerby, "Base station

placement in indoor wireless systems using binary integer programming," *IEE Proceedings Communications*, vol. 153, no. 5, pp. 771-778, 2006.

[10] Z. Jin, X. Wu, Y. Shu, and F. Liu, "Optimal placement of multiple 802.11B APS in a wireless classroom," presented at IEEE Canadian Conference on Electrical and Computer Engineering, 2003, pp. 741-744.

[11] K. Papagiannaki, M. Yarvis, and W. S. Conner, "Experimental Characterization of Home Wireless Networks and Design Implications," presented at Proceedings IEEE International Conference on Computer Communications, 2006, pp. 1-13.

[12] H. Lim, L. C. Kung, J. C. Hou, and H. Luo, "Zero-Configuration, Robust Indoor Localization: Theory and Experimentation," presented at Proceedings 25th IEEE International Conference on Computer Communications, 2006, pp. 1-12.

[13] IEEE 80211 Standard 1999 Edition (R2003), "Information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks- Specific requirements- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,", 2003.

[14] M. S. Gast, *802.11 Wireless Networks - The Definitive Guide*, second ed. Sebastopol: O'Reilly Media, Inc., 2005.

[15] M. J. Ho, M. S. Rawles, M. Vrijkorte, and L. Fei, "RF challenges for 2.4 and 5 GHz WLAN deployment and design," presented at IEEE Wireless Communications and Networking Conference, 2002, pp. 783-788.

[16] J. Khan and A. Khwaja, *Building Secure Wireless Networks with 802.11*. Indianapolis: Wiley Publishing, Inc., 2003.

[17] N. Prasad, A. Prasad, A. Kamerman, H. Moelard, and L. Brederveld, *WLAN Systems and Wireless IP for Next Generation Communications*. Boston: Artech House, 2002.

[18] R. Olexa, *Implementing 802.11, 802.16 and 802.20 wireless networks : planning, troubleshooting, and maintenance*. Boston: Amsterdam, 2004.

[19] IEEE 802.11a Standard, "Supplement to IEEE standard for information technology telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements. Part 11: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: high-speed physical layer in the 5 GHz band," 1999.

[20] IEEE 802.11b Standard, "Supplement To IEEE Standard For Information Technology- Telecommunications And Information Exchange Between Systems- Local And Metropolitan Area Networks- Specific Requirements- Part 11: Wireless LAN Medium Access Control (MAC) And Physical Layer (PHY) Specifications: Higher-speed Physical Layer Extension In The 2.4 GHz Band,"

2000.
[21] IEEE 802.11g Standard, "IEEE Std 802.11g-2003 (Amendment to IEEE Std 802.11, 1999 Edn. (Reaff 2003) as amended by IEEE Stds 802.11a-1999, 802.11b-1999, 802.11b-1999/Cor 1-2001, and 802.11d-2001)," 2003.
[22] Y. Bejerano and R. S. Bhatia, "MiFi: a framework for fairness and QoS assurance for current IEEE 802.11 networks with multiple access points," *IEEE/ACM Transactions on Networking*, vol. 14, no. 4, pp. 849-862, 2006.
[23] T. Murakami, Y. Matsumoto, K. Fujii, and Y. Yamanaka, "Effects of multi-path propagation on microwave oven interference in wireless systems," presented at 2003 IEEE International Symposium on Electromagnetic Compatibility, 2003, pp. 749-752.
[24] T. Murakami, Y. Matsumoto, K. Fujii, A. Sugiura, and Y. Yamanaka, "Propagation characteristics of the microwave oven noise interfering with wireless systems in the 2.4 GHz band," presented at 14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications, 2003, pp. 2726-2729.
[25] A. Kamerman and N. Erkocevic, "Microwave oven interference on wireless LANs operating in the 2.4 GHz ISM band," presented at The 8th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 1997, pp. 1221-1227.
[26] S. Miyamoto and N. Morinaga, "Performance of radio communication systems under microwave oven interference environment," 1997, pp. 308-311.
[27] H. Li, M. Syed, and Y.-D. Yao, "Outage performance of a hybrid DS/FH spread-spectrum signal in an ISM band," *International Journal of Network Management*, vol. 16, no. 2, pp. 115-129, 2006.
[28] N. Golmie, R. E. V. Dyck, A. Soltanian, A. Tonnerre, and O. Rébala, "Interference evaluation of Bluetooth and IEEE 802.11b systems," *Wireless Networks*, vol. 9, no. 3, pp. 201-211, 2003.
[29] I. Howitt, "Bluetooth performance in the presence of 802.11b WLAN," *IEEE Transactions on Vehicular Technology*, vol. 51, no. 6, pp. 1640-1651, 2002.
[30] M. Kato, H. Okura, K. Ito, and S. Tasaka, "Experimental assessment of media synchronization quality in IEEE 802.11 b under Bluetooth interference," presented at 14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications, 2003, pp. 2683-2689.
[31] L. He and W. Yin, "Interference evaluation of Bluetooth and IEEE 802.11b systems," presented at 4th International Conference on Microwave and Millimeter Wave Technology, 2004, pp. 931-934.
[32] C. F. Chiasserini and R. R. Rao, "Coexistence mechanisms for interference mitigation in the 2.4-GHz ISM band," *IEEE Transactions on Wireless*

*Communications*, vol. 2, no. 5, pp. 964-975, 2003.

[33] J. H. Jo and N. Jayant, "Performance evaluation of multiple IEEE 802.11b WLAN stations in the presence of Bluetooth radio interference," presented at IEEE International Conference on Communications, 2003, pp. 1163-1168.

[34] IEEE80211, "IEEE Std 802.11-1997 Information Technology- telecommunications And Information exchange Between Systems-Local And Metropolitan Area Networks-specific Requirements-part 11: Wireless Lan Medium Access Control (MAC) And Physical Layer (PHY) Specifications," *IEEE Std 802.11-1997*, no. i-445, 1997.

[35] J. A. Park, S. K. Park, P. D. Cho, and K. R. Cho, "Analysis of spectrum channel assignment for IEEE 802.11b wireless LAN," presented at The 5th International Symposium on Wireless Personal Multimedia Communications, 2002, pp. 1073-1077.

[36] A. Prasad and N. Prasad, *802.11 WLANs and IP networking : security, QoS, and mobility*. Boston: Artech House, 2005.

[37] X. Xu, C. Zhang, and X. Lin, "Using different orthogonal code sets for CCK modulation to mitigate co-channel interference among WLANs," presented at IEEE International Symposium on Communications and Information Technology, 2005, pp. 885-888.

[38] N. Reid and R. Seide, *802.11 (Wi-Fi) Networking Handbook*. Berkeley: McGraw-Hill, 2003.

[39] M. Rodring, C. Reis, R. Mahajan, D. Wetherall, and J. Zahorjan, "Measurement-based characterization of 802.11 in a hotspot setting," presented at Proceedings of the 2006 conference on Applications, technologies, architectures, and protocols for computer communications, 2006, pp. 51-62.

[40] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, 2000.

[41] K. Chebrolu, B. Raman, and S. Sen, "Long-distance 802.11b links: performance measurements and experience " presented at Proceedings of the 12th annual international conference on Mobile computing and networking 2006, pp. 74-85.

[42] T. C. Hou, L. F. Tsao, and H. C. Liu, "Analyzing the throughput of IEEE 802.11 DCF scheme with hidden nodes," presented at IEEE 58th Vehicular Technology Conference, 2003, pp. 2870-2874.

[43] X. Ling and K. L. Yeung, "Joint access point placement and channel assignment for 802.11 wireless LANs," presented at IEEE Wireless Communications and Networking Conference, 2005, pp. 1583-1588.

[44] H. Wu, F. Zhu, Q. Zhang, and Z. Niu, "Analysis of IEEE 802.11 DCF with

Hidden Terminals," presented at IEEE Global Telecommunications Conference, 2006, pp. 1-5.
[45] A. Kamerman and G. Aben, "Net throughput with IEEE 802.11 wireless LANs," presented at IEEE Wireless Communications and Networking Conference, 2000, pp. 747-752.
[46] D. Pham, Y. A. Sekercioglu, and G. K. Egan, "Performance of IEEE 802.11b Wireless Links: An Experimental Study," presented at IEEE Region 10 Conference, 2005, pp. 1-6.
[47] C. Hoene, A. Gunther, and A. Wolisz, "Measuring the impact of slow user motion on packet loss and delay over IEEE 802.11b wireless links," presented at The 28th Annual IEEE International Conference on Local Computer Networks, 2003, pp. 652-662.
[48] D. B. Green and M. S. Obaidat, "An accurate line of sight propagation performance model for ad-hoc 802.11 wireless LAN (WLAN) devices," presented at IEEE International Conference on Communications, 2002, pp. 3424-3428.
[49] G. Anastasi, E. Borgia, M. Conti, and E. Gregori, "Wi-Fi in ad hoc mode: a measurement study," presented at Proceedings of the Second IEEE Annual Conference on Pervasive Computing and Communications, 2004, pp. 145-154.
[50] S. Garg and M. Kappes, "Admission control for VoIP traffic in IEEE 802.11 networks," presented at IEEE Global Telecommunications Conference, 2003, pp. 3514-3518.
[51] H. W. Tseng, A. C. Pang, C. F. Kuo, and S. T. Sheu, "Efficient and fast retransmission for wireless networks," *Computer Communications*, vol. 29, no. 15, pp. 2964-2974, 2006.
[52] K. S. Butterworth, K. W. Sowerby, and A. G. Williamson, "Base station placement for in-building mobile communication systems to yield high capacity and efficiency," *IEEE Transactions on Communications*, vol. 48, no. 4, pp. 658-669, 2000.
[53] K. W. Cheung and R. D. Murch, "Optimising indoor base-station locations in coverage- and interference-limited indoor environments," presented at IEE Proceedings Communications, 1998, pp. 445-450.
[54] T. Fruhwirth and P. Brisset, "Placing base stations in wireless indoor communication networks," *IEEE Intelligent Systems and Their Applications*, vol. 15, no. 1, pp. 49-53, 2000.
[55] M. Lindstrom, "Base station placement in asymmetric TDD mode systems in a Manhattan environment," presented at 2004 IEEE 59th Vehicular Technology Conference, 2004, pp. 1968-1972.

[56] J. K. L. Wong, M. J. Neve, and K. W. Sowerby, "Optimisation strategy for wireless communications system planning using linear programming," *IEE Electronics Letters*, vol. 37, no. 17, pp. 1086-1087, 2001.

[57] WirelessMon - Wireless 802.11 Wi-Fi Monitoring Software, Access on 25 February, 2007, from http://www.passmark.com/products/wirelessmonitor.html.

[58] M. Kappes, A. S. Krishnakumar, and P. Krishnan, "Estimating signal strength coverage for a wireless access point," presented at IEEE Global Telecommunications Conference, 2004, pp. 3264-3269.

[59] D. Stamatelos and A. Ephremides, "Spectral efficiency and optimal base placement for indoor wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 4, pp. 651-661, 1996.

[60] M. J. Neve and K. W. Sowerby, "Optimising the performance of indoor wireless communication systems," IEEE 49th Vehicular Technology Conference, 1999, pp. 968-972.

[61] M. Kobayashi, S. Haruyama, R. Kohno, and M. Nakagawa, "Optimal access point placement in simultaneous broadcast system using OFDM for indoor wireless LAN," presented at The 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2000, pp. 200-204.

[62] R. C. Rodrigues, G. R. Mateus, and A. A. F. Loureiro, "Optimal base station placement and fixed channel assignment applied to wireless local area network projects," presented at IEEE International Conference on Networks, 1999, pp. 186-192.

[63] T. Wang and H. H. Refai, "The development of an empirical delay model for IEEE 802.11 b/g based on SNR measurements," presented at 2005 International Conference on Wireless Networks, Communications and Mobile Computing, 2005, pp. 381-385.

[64] W. Ge, Y. Shu, L. Zhang, L. Hao, and W. W. Yang, "Measurement and Analysis of TCP Performance in IEEE 802.11 Wireless Network," presented at Canadian Conference on Electrical and Computer Engineering, 2006, pp. 1846-1849.

[65] D. Aguayo, J. Bicket, S. Biswas, G. Judd, R. Morris, and C. Mellon, "Link-level Measurements from an 802.11b Mesh Network," presented at Proceedings of the 2004 conference on Applications, technologies, architectures, and protocols for computer communications, 2004, pp. 121-132.

[66] K. K. Wong and T. O'Farrell, "Coverage of 802.11g WLANs in the presence of Bluetooth interference," presented at 14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications, 2003, pp. 2027-2031.

[67] C. Rose, S. Ulukus, and R. D. Yates, "Wireless systems and interference avoidance," *IEEE Transactions on Wireless Communications*, vol. 1, no. 3, pp.

415-428, 2002.

[68] J. K. L. Wong, M. J. Neve, and K. W. Sowerby, "Uplink and downlink SIR analysis for base station placement," presented at The 57th IEEE Semiannual Vehicular Technology Conference, 2003, pp. 112-116.

[69] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "Influence of channel BER on IEEE 802.11 DCF," *IEE Electronics Letters*, vol. 39, no. 23, pp. 1687-1689, 2003.

[70] M. N. Smadi and B. Szabados, "Error-recovery service for the IEEE 802.11b protocol," *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 4, pp. 1377-1382, 2006.

[71] E. Pelletta and H. Velayos, "Performance measurements of the saturation throughput in IEEE 802.11 access points," presented at Third International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks, 2005, pp. 129-138.

[72] M. Boulmalf, H. El-Sayed, and A. Soufyane, "Measured throughput and SNR of IEEE 802.11g in a small enterprise environment," presented at IEEE Vehicular Technology Conference, 2005, pp. 1333-1337.

[73] J. Zhu, B. Metzler, X. Guo, and Y. Liu, "Adaptive CSMA for Scalable Network Capacity in High-Density WLAN: A Hardware Prototyping Approach," presented at 25th IEEE International Conference on Computer Communications, INFOCOM 2006, 2006, pp. 1-10.

[74] K. Kaemarungsi and P. Krishnamurthy, "Properties of indoor received signal strength for WLAN location fingerprinting," presented at The First Annual International Conference on Mobile and Ubiquitous Systems: Networking and Services, 2004, pp. 14-23.

[75] T. Locher, R. Wattenhofer, and A. Zollinger, "Received-signal-strength-based logical positioning resilient to signal fluctuation," presented at Sixth International Conference on Software Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing and First ACIS International Workshop on Self-Assembling Wireless Networks, 2005, pp. 396-402.

[76] M. J. Johnson, J. S. King, R. S. Shryock, J. Kiviniemi, and T. Heinonen, "Analysis of a signal strength based positioning system for commercial environments," presented at 2005 the Second IEEE Consumer Communications and Networking Conference, 2005, pp. 533-538.

[77] M. Youssef and A. Agrawala, "The Horus WLAN location determination system," presented at Proceedings of the 3rd international conference on Mobile systems, applications, and services, Seattle, Washington 2005, pp. 205-218.

[78] G. I. Wassi, C. Despins, D. Grenier, and C. Nerguizian, "Indoor location using

received signal strength of IEEE 802.11b access point," presented at Canadian Conference on Electrical and Computer Engineering, 2005, pp. 1367-1370.

[79] G. V. Zdruba, M. Huber, F. A. Karnangar, and I. Chlarntac, "Monte Carlo sampling based in-home location tracking with minimal RF infrastructure requirements," presented at IEEE Global Telecommunications Conference, 2004, pp. 3624-3629.

[80] K. Kaemarungsi, "Distribution of WLAN received signal strength indication for indoor location determination," presented at 2006 1st International Symposium on Wireless Pervasive Computing, 2006, pp. 6-12.

[81] S. Ito and N. Kawaguchi, "Data Correction Method Using Ideal Wireless LAN Model in Positioning System," presented at IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications, 2006, pp. 1-5.

[82] C. Xinjie, "Network simulations with OPNET," presented at Simulation Conference Proceedings, 1999, pp. 307-314.

[83] The Network Simulator 2, Access on 12, March, 2007, from http://www.isi.edu/nsnam/ns/.

[84] OPNET, Access on 12, March, 2007, from http://www.opnet.com/.

[85] S. Gopal and D. Raychaudhuri, "Experimental evaluation of the TCP simultaneous-send problem in 802.11 wireless local area networks," presented at Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis, 2005, pp. 23-28.

[86] D. Johnson, T. Stack, R. Fish, D. M. Flickinger, L. Stoller, R. Ricci, and J. Lepreau, "Mobile Emulab: A Robotic Wireless and Sensor Network Testbed," presented at The 25th IEEE International Conference on Computer Communications (INFOCOM 2006), 2006, pp. 1-12.

[87] J. A. Park, S. K. Park, D. H. Kim, P. D. Cho, and K. R. Cho, "Experiments on radio interference between wireless LAN and other radio devices on a 2.4 GHz ISM band," presented at The 57th IEEE Semiannual Vehicular Technology Conference, 2003, pp. 1798-1801.

[88] N. Chen, J. K. Chen, and T. S. Rappaport, "Measured Traffic Statistics and Throughput of IEEE 802.11b Public WLAN Hotspots with Three Different Applications," *IEEE Transactions on Wireless Communications*, vol. 5, no. 11, pp. 3296-3305, 2006.

[89] F. Li, M. Li, R. Lu, H. Wu, C. M., and K. R., "Tools and Techniques for Measurement of IEEE 802.11 Wireless Networks," presented at The 4th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, 2006, pp. 1-8.

[90] K. Jamieson, B. Hull, A. Miu, and H. Balakrishnan, "Understanding the

real-world performance of carrier sense," presented at Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis, 2005, pp. 52-57.

[91] D-Link Wireless Access Point (802.11 b/g) DWL-2100AP, Access on 26 February, 2007 from http://www.dlink.com/products/?pid=292.

[92] D-Link Wireless USB Adapter (802.11 b/g) DWL-G132, Access on 26 February, 2007 from http://www.dlink.com/products/?pid=358.

[93] D-Link 2.4 GHz Omni-Directional 7dBi Indoor Antenna ANT24-0700, Access on 26 February, 2007 from http://www.dlink.com/products/?pid=416.

[94] J. FitzGerald and A. Dennis, *Business Data Communications and Networking, 9th Edition*. Hoboken, NJ: John Wiley & Sons, 2006.

[95] N. I. Sarkar and K. W. Sowerby, "Wi-Fi Performance Measurements in the Crowded Office Environment: a Case Study," presented at International Conference on Communication Technology, 2006, pp. 37-40.

[96] J. D. McCabe, *Network Analysis, Architecture, and Design Second Edition*, Second Edition ed. San Francisco: Morgan Kaufmann Publishers, 2003.

[97] Xtra Wireless Plans, Access on 24, May, 2007 from http://jetstream.xtra.co.nz/chm/0,6858,203313-202321,00.html.

# Appendix A
# Preliminary Experimental Results

## 1. The Ad-Hoc Mode Measurement in the Meeting Room

| File Size (MB) | | Distance: 1m RSS: -45 dBm | | Distance: 2m RSS: -41dBm | | Distance: 3m RSS: -47 dBm | |
|---|---|---|---|---|---|---|---|
| | | Time (second) | Throughput (Mbps) | Time (second) | Throughput (Mbps) | Time (second) | Throughput (Mbps) |
| Data | 10.9 | 16.5 | 5.319 | 15.1 | 5.812 | 16.4 | 5.352 |
| | 21.9 | 32.1 | 5.468 | 30.7 | 5.718 | 31.8 | 5.520 |
| | 32.9 | 48.2 | 5.463 | 46.5 | 5.662 | 46.8 | 5.626 |
| | 43.8 | 65 | 5.401 | 62.7 | 5.599 | 63.1 | 5.564 |
| | 54.8 | 80.5 | 5.451 | 77.8 | 5.640 | 78.2 | 5.612 |
| | 65.8 | 96.7 | 5.446 | 93.5 | 5.632 | 95.2 | 5.531 |
| | 76.8 | 114.2 | 5.380 | 110.8 | 5.545 | 111.3 | 5.520 |
| | 87.8 | 128.8 | 5.451 | 126.9 | 5.533 | 127.2 | 5.520 |
| | 98.7 | 146 | 5.410 | 143.6 | 5.501 | 144.5 | 5.466 |
| | 109.7 | 161.4 | 5.438 | 156.8 | 5.597 | 158.6 | 5.534 |
| | 120.7 | 175.7 | 5.495 | 171.3 | 5.636 | 173.9 | 5.552 |
| | 131.6 | 191 | 5.514 | 186.1 | 5.659 | 190.2 | 5.537 |
| | 142.6 | 209.2 | 5.454 | 203.5 | 5.607 | 204.7 | 5.574 |
| | 153.6 | 226.4 | 5.427 | 218.9 | 5.613 | 220.6 | 5.570 |
| | 164.6 | 240.7 | 5.469 | 232.2 | 5.670 | 237.3 | 5.548 |
| | 274 | 411.3 | 5.335 | 386.9 | 5.671 | 390.2 | 5.623 |
| Audio: 263 | | 385 | 5.480 | 374.1 | 5.640 | 375.1 | 5.625 |
| Video: 256 | | 375.4 | 5.467 | 362.1 | 5.668 | 364 | 5.638 |
| Throughput | | 5.437 | | 5.634 | | 5.551 | |
| Average Throughput | | 5.540 | | | | | |

Table A.1: Numerical results for ad-hoc mode.

## 2. AP Mode Measurement in the Meeting Room

| File Size / Time / Throughput | | Distance: 1m RSS: -47 dBm | | Distance: 2m RSS: -43 dBm | |
|---|---|---|---|---|---|
| | | Time (second) | Throughput (Mbps) | Time (second) | Throughput (Mbps) |
| Data | 109 MB | 107.7 | 8.149 | 83.9 | 10.461 |
| | 274 MB | 271.6 | 8.079 | 212.9 | 10.306 |
| Audio: 263 MB | | 258.9 | 8.150 | 202.4 | 10.425 |
| Video: 256MB | | 248.7 | 8.252 | 200.5 | 10.236 |
| Average Throughput | | 8.157 | | 10.357 | |

Table A.2: Numerical results for AP mode.

## 3. WDS with AP Mode Measurement in the Meeting Room

| File Size / Time / Throughput | | Distance: 2m, RSS: -43 dBm | |
|---|---|---|---|
| | | Time (second) | Throughput (Mbps) |
| Data | 109 MB | 151.5 | 5.793 |
| | 274 MB | 382.7 | 5.733 |
| Audio: 263 MB | | 369.1 | 5.717 |
| Video: 256MB | | 355.2 | 5.778 |
| Average Throughput | | | 5.755 |

Table A.3: Numerical results for WDS with AP mode.

## 4. AP Mode with Ethernet Measurement in the Meeting Room

| File Size / Time / Throughput | | Distance: 2Meters, RSS: -43 dBm | |
|---|---|---|---|
| | | Time (second) | Throughput (Mbps) |
| Data | 109 MB | 78.7 | 11.152 |
| | 274 MB | 182.3 | 12.036 |
| Audio: 263 MB | | 168.7 | 12.507 |
| Video: 256MB | | 174.6 | 11.755 |
| Average Throughput | | | 11.863 |

Table A.4: Numerical results for AP Mode with Ethernet connection.

## 5. WDS Mode Measurement in the Meeting Room

| File Size / Time / Throughput | | Distance: 2Meters | |
|---|---|---|---|
| | | Time (second) | Throughput (Mbps) |
| Data | 109 MB | 46.7 | 18.794 |
| | 274 MB | 113.9 | 19.264 |
| Audio: 263 MB | | 108.4 | 19.465 |
| Video: 256MB | | 104.7 | 19.603 |
| Average Throughput | | | 19.281 |

Table A.5: Numerical results for WDS Mode.

## 6. Throughput Comparison with Different AP Configuration

| File Size / Modes | | AP Mode-1M (Mbps) | AP Mode -2M (Mbps) | WDS with AP (Mbps) | AP Mode with Ethernet (Mbps) | WDS Mode (Mbps) |
|---|---|---|---|---|---|---|
| RSS (dBm) | | -47 | -43 | -43 | -43 | N/A |
| Data | 109 MB | 8.149 | 10.461 | 5.793 | 11.152 | 18.794 |
| | 274 MB | 8.079 | 10.306 | 5.733 | 12.036 | 19.264 |
| Audio: 263 MB | | 8.150 | 10.425 | 5.717 | 12.507 | 19.465 |
| Video: 256MB | | 8.252 | 10.236 | 5.778 | 11.755 | 19.603 |
| Average Throughput | | 8.157 | 10.357 | 5.755 | 11.863 | 19.281 |

Table A.6: Throughput comparison with different AP configuration.

## 7. The Ad-Hoc Mode Measurement on the Floor

| TX at A<br>RX Position (Meter) | Distance from TX (Meter) | Signal Strength (dBm) | Time (Seconds) | Throughput (Mbps) |
|---|---|---|---|---|
| 1 | 1 | -43 | 15.8 | 5.555 |
| 2 | 2 | -48 | 15.6 | 5.626 |
| 3 | 3 | -54 | 16.3 | 5.384 |
| 4 | 4 | -51 | 15.9 | 5.520 |
| 5 | 5 | -49 | 15.9 | 5.520 |
| 6 | 6 | -47 | 15.8 | 5.555 |
| 7 | 7 | -49 | 16.0 | 5.485 |
| 8 | 8 | -55 | 15.8 | 5.555 |
| 9 | 9 | -55 | 16.1 | 5.451 |
| 10 | 10 | -57 | 16.3 | 5.384 |
| 15 | 15 | -65 | 15.9 | 5.520 |
| 20 | 20 | -67 | 16.0 | 5.485 |
| 25 | 25 | -65 | 15.9 | 5.520 |
| 30 | 30 | -66 | 15.9 | 5.520 |
| 32M | 32 | -62 | 15.9 | 5.520 |
| **Average Throughput** | | | | 5.507 |

Table A.7: Numerical results for an ad-hoc mode with LOS.

| TX at A<br>RX Position | Distance from TX (Meter) | Signal Strength (dBm) | Time (Second) | Throughput (Mbps) |
|---|---|---|---|---|
| D | 13.42 | -65 | 16.5 | 5.319 |
| E | 16.28 | -65 | 17.3 | 5.073 |
| F | 12.53 | -60 | 18.6 | 4.719 |
| L | 19.24 | -81 | 113.2 | 0.775 |
| M | 23.31 | -74 | 57.7 | 1.521 |
| (J-1m)J-K | 23.05 | -70 | 20.0 | 4.388 |
| (J-2m)J-K | 23.14 | -71 | 42.3 | 2.075 |
| (J-3m)J-K | 23.26 | -74 | 64.2 | 1.367 |
| K | 23.77 | -78 | 65.7 | 1.336 |
| N | 25.94 | -75 | 72.5 | 1.211 |

| | | | | |
|---|---|---|---|---|
| (N-1m)N-O | 27.73 | -83 | 86.7 | 1.012 |
| (N-2m)N-O | 28.64 | -84 | 109.2 | 0.804 |
| (N-3m)N-O | 29.55 | -83 | 97.6 | 0.899 |
| O | 30.00 | -85 | 172.3 | 0.509 |
| (P-3m)O-P | 30.92 | -85 | 185.2 | 0.474 |
| (P-2m)O-P | 31.85 | -86 | 214.5 | 0.409 |
| (P-1m)O-P | 32.78 | Block | N/A | N/A |
| P | 34.18 | Block | N/A | N/A |
| (P-1m) P-Q | 33.68 | Block | N/A | N/A |
| (P-2m)P-Q | 33.38 | -85 | 203.2 | 0.432 |
| (P-3m)P-Q | 33.11 | -88 | 289.2 | 0.303 |
| Q | 32.56 | -86 | 193.7 | 0.453 |
| (R-4m)Q-R | 32.31 | -79 | 87.6 | 1.002 |
| (R-3m)Q-R | 32.19 | -78 | 61.7 | 1.422 |
| (R-2m)Q-R | 32.10 | -79 | 74.8 | 1.173 |
| (R-1m)Q-R | 32.04 | -71 | 41.5 | 2.115 |

Table A.8: Numerical results for an ad-hoc mode with NLOS.

# Appendix B
# Phase 1 Experimental Results

## 1. Access Point at Position “A”

| AP at A | | TX at A2 Position | | File Size: 10.9MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **B** | 6.00 | -52 | 9 | 9.752 | LOS |
| **C** | 12.00 | -60 | 8.9 | 9.861 | LOS |
| **(C-2m)C-D** | 12.17 | -67 | 9.3 | 9.437 | NLOS |
| **(C-3m)C-D** | 12.37 | -66 | 9.1 | 9.645 | NLOS |
| **(C-4m)C-D** | 12.65 | -67 | 9.6 | 9.142 | NLOS |
| **D** | 13.42 | -71 | 10 | 8.777 | NLOS |
| **E** | 16.28 | -70 | 11.8 | 7.438 | NLOS |
| **F** | 12.53 | -72 | 12.6 | 6.965 | NLOS |
| **(H-3.5m)F-H** | 11.54 | -68 | 10.8 | 8.126 | NLOS |
| **(H-2.5m)F-H** | 11.28 | -62 | 9.2 | 9.540 | NLOS |
| **(H-1.5m)F-H** | 11.10 | -61 | 9.7 | 9.048 | NLOS |
| **H** | 11.00 | -59 | 8.7 | 10.088 | LOS |
| **G** | 6.00 | -53 | 8.7 | 10.088 | LOS |
| **I** | 17.00 | -61 | 8.5 | 10.325 | LOS |
| **L** | 19.24 | -77 | 32 | 2.743 | NLOS |
| **M** | 23.31 | -76 | 28 | 3.134 | NLOS |
| **J** | 23.00 | -62 | 9.4 | 9.337 | LOS |
| **(J-1.5m)J-K** | 23.05 | -72 | 24.2 | 3.627 | NLOS |
| **(J-2.5m)J-K** | 23.14 | -68 | 20.2 | 4.345 | NLOS |
| **(J-3.5m)J-K** | 23.26 | -76 | 26.4 | 3.324 | NLOS |
| **K** | 23.77 | -79 | 29.3 | 2.995 | NLOS |
| **(N-3.5m)K-N** | 24.52 | -79 | 30.2 | 2.906 | NLOS |
| **(N-2.5m)K-N** | 24.88 | -79 | 34.6 | 2.537 | NLOS |
| **(N-1.5m)K-N** | 25.28 | -82 | 42.3 | 2.075 | NLOS |
| **N** | 25.94 | -81 | 50.4 | 1.741 | NLOS |
| **(N-2m)N-O** | 27.73 | -87 | 115.2 | 0.762 | NLOS |
| **(N-3m)N-O** | 28.64 | -87 | 133.2 | 0.659 | NLOS |
| **O** | 30.00 | -90 | 223.2 | 0.393 | NLOS |
| **(P-3.5m)O-P** | 30.92 | -90 | 208.2 | 0.422 | NLOS |
| **(P-2.5m)O-P** | 31.85 | -88 | 210.2 | 0.418 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **(P-1.5m)O-P** | 32.78 | -86 | 193.6 | 0.453 | NLOS |
| **P** | 34.18 | -84 | 140.1 | 0.626 | NLOS |
| **(P-1.5m)P-Q** | 33.68 | -84 | 102.3 | 0.858 | NLOS |
| **(P-2.5m)P-Q** | 33.38 | -87 | 156.7 | 0.560 | NLOS |
| **(P-3.5m)P-Q** | 33.11 | -88 | 185.6 | 0.473 | NLOS |
| **Q** | 32.56 | -87 | 144.4 | 0.608 | NLOS |
| **(R-4.5m)Q-R** | 32.31 | -82 | 127 | 0.691 | NLOS |
| **(R-3.5m)Q-R** | 32.19 | -75 | 67.1 | 1.308 | NLOS |
| **(R-2.5m)Q-R** | 32.10 | -82 | 81.3 | 1.080 | NLOS |
| **(R-1.5m)Q-R** | 32.04 | -70 | 28.5 | 3.079 | NLOS |
| **R** | 32.00 | -65 | 16.5 | 5.319 | LOS |
| **S** | 27.50 | -63 | 12.1 | 7.253 | LOS |

Table B.1: Numerical results for AP at position “A”.

## 2. Access Point at Position “G”

| **AP at G** | | **TX at G2 Position** | | **File Size: 10.9MB** | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 6.00 | -60.00 | 8.4 | 10.448 | LOS |
| **(A-1.5m)A-B** | 6.18 | -51.00 | 8.4 | 10.448 | NLOS |
| **(A-2.5m)A-B** | 6.50 | -57.00 | 9.1 | 9.645 | NLOS |
| **(A-3.5m)A-B** | 6.95 | -56.00 | 8.9 | 9.861 | NLOS |
| **B** | 8.49 | -65.00 | 9.3 | 9.437 | NLOS |
| **(C-4m)B-C** | 10.00 | -64.00 | 9.4 | 9.337 | NLOS |
| **(C-3m)B-C** | 10.82 | -63.00 | 9.6 | 9.142 | NLOS |
| **(C-2m)B-C** | 11.66 | -66.00 | 10.7 | 8.202 | NLOS |
| **C** | 13.42 | -69.00 | 15.6 | 5.626 | NLOS |
| **(C-2m)C-D** | 12.65 | -70.00 | 11.6 | 7.566 | NLOS |
| **(C-3m)C-D** | 12.37 | -67.00 | 11.2 | 7.836 | NLOS |
| **D** | 12.00 | -65.00 | 10.4 | 8.439 | NLOS |
| **(E-3m)D-E** | 12.17 | -61.00 | 9.9 | 8.865 | NLOS |
| **(E-2m)D-E** | 12.37 | -63.00 | 10.2 | 8.604 | NLOS |
| **E** | 13.00 | -64.00 | 11.5 | 7.632 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **F** | 7.81 | -63.00 | 10 | 8.777 | NLOS |
| **(H-2.5m)F-H** | 5.59 | -61.00 | 9.5 | 9.238 | NLOS |
| **(H-1.5m)F-H** | 5.22 | -54.00 | 8.3 | 10.574 | NLOS |
| **H** | 5.00 | -55.00 | 8 | 10.971 | LOS |
| **I** | 11.00 | -54.00 | 8.6 | 10.205 | LOS |
| **L** | 14.21 | -75.00 | 14.3 | 6.137 | NLOS |
| **M** | 17.92 | -74.00 | 20.4 | 4.302 | NLOS |
| **J** | 17.00 | -62.00 | 9.5 | 9.238 | LOS |
| **(J-1.5m)J-K** | 17.07 | -71.00 | 13.2 | 6.649 | NLOS |
| **(J-2.5m)J-K** | 17.18 | -66.00 | 15.2 | 5.774 | NLOS |
| **(J-3.5m)J-K** | 17.36 | -75.00 | 19.2 | 4.571 | NLOS |
| **K** | 18.03 | -77.00 | 22.6 | 3.883 | NLOS |
| **(N-3.5m)K-N** | 19.01 | -76.00 | 26.3 | 3.337 | NLOS |
| **(N-2.5m)K-N** | 19.47 | -77.00 | 33.6 | 2.612 | NLOS |
| **(N-1.5m)K-N** | 19.98 | -79.00 | 35.2 | 2.493 | NLOS |
| **N** | 20.81 | -82.00 | 42.2 | 2.080 | NLOS |
| **(N-2m)N-O** | 22.47 | -84.00 | 67.5 | 1.300 | NLOS |
| **(N-3m)N-O** | 23.32 | -85.00 | 83.2 | 1.055 | NLOS |
| **(N-4m)N-O** | 24.19 | -85.00 | 92.3 | 0.951 | NLOS |
| **O** | 24.62 | -88.00 | 110.6 | 0.794 | NLOS |
| **(P-3.5m)O-P** | 25.50 | -87.00 | 182.7 | 0.480 | NLOS |
| **(P-2.5m)O-P** | 26.39 | -87.00 | 156.2 | 0.562 | NLOS |
| **(P-1.5m)O-P** | 27.28 | -90.00 | 234 | 0.375 | NLOS |
| **P** | 28.64 | -83.00 | 121.5 | 0.722 | NLOS |
| **(P-1.5m)P-Q** | 28.04 | -90.00 | 218.5 | 0.402 | NLOS |
| **(P-2.5m)P-Q** | 27.68 | -82.00 | 80.8 | 1.086 | NLOS |
| **(P-3.5m)P-Q** | 27.35 | -81.00 | 57.3 | 1.532 | NLOS |
| **Q** | 26.68 | -81.00 | 29.1 | 3.016 | NLOS |
| **(R-3.5m)Q-R** | 26.23 | -75.00 | 21.4 | 4.101 | NLOS |
| **(R-2.5m)Q-R** | 26.12 | -71.00 | 17.2 | 5.103 | NLOS |
| **(R-1.5m)Q-R** | 26.04 | -70.00 | 14.3 | 6.137 | NLOS |
| **R** | 26.00 | -64.00 | 9.6 | 9.142 | LOS |
| **S** | 21.50 | -59.00 | 9.4 | 9.337 | LOS |

Table B.2: Numerical results for AP at position “G”.

## 3. Access Point at Position “E-3M”

| AP at “E-3m” | | TX at E2 Position | | File Size: 10.9 MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 14.21 | -73 | 12.6 | 6.965 | NLOS |
| **(A-1.5m)A-B** | 13.31 | -71 | 11.8 | 7.438 | NLOS |
| **(A-2.5m)A-B** | 12.78 | -75 | 13.2 | 6.649 | NLOS |
| **B** | 11.40 | -68 | 9.5 | 9.238 | NLOS |
| **(C-3m)B-C** | 11.00 | -72 | 9.7 | 9.048 | NLOS |
| **(C-2m)B-C** | 11.05 | -73 | 10.9 | 8.052 | NLOS |
| **C** | 11.40 | -60 | 8.2 | 10.703 | NLOS |
| **(C-2m)C-D** | 9.49 | -63 | 8.5 | 10.325 | NLOS |
| **(C-3m)C-D** | 8.54 | -62 | 9.8 | 8.956 | NLOS |
| **D** | 5.83 | -62 | 9.4 | 9.337 | NLOS |
| **E** | 3.00 | -43 | 8.2 | 10.703 | LOS |
| **F** | 3.00 | -55 | 8.1 | 10.835 | LOS |
| **G** | 10.30 | -63 | 8.5 | 10.325 | NLOS |
| **(H-3m)G-H** | 9.49 | -63 | 8.3 | 10.574 | NLOS |
| **(H-2m)G-H** | 9.22 | -57 | 8.1 | 10.835 | NLOS |
| **H** | 9.00 | -60 | 8 | 10.971 | LOS |
| **I** | 10.82 | -64 | 9.2 | 9.540 | NLOS |
| **L** | 6.00 | -55 | 8.7 | 10.008 | LOS |
| **M** | 10.50 | -57 | 9.5 | 9.238 | LOS |
| **J** | 15.00 | -68 | 10.5 | 8.359 | NLOS |
| **(J-1.5m)J-K** | 14.15 | -69 | 10.9 | 8.052 | NLOS |
| **(J-2.5m)J-K** | 13.65 | -66 | 11.3 | 7.767 | NLOS |
| **K** | 12.37 | -62 | 15.2 | 5.774 | NLOS |
| **(N-2.5m)K-N** | 12.04 | -59 | 11.8 | 7.438 | NLOS |
| **(N-1.5m)K-N** | 12.17 | -63 | 12.1 | 7.253 | NLOS |
| **N** | 12.37 | -66 | 12.8 | 6.857 | NLOS |
| **(N-2m)N-O** | 14.32 | -71 | 20.5 | 4.281 | NLOS |
| **(N-3m)N-O** | 15.30 | -68 | 17.4 | 5.044 | NLOS |
| **O** | 16.77 | -71 | 27.4 | 3.203 | NLOS |
| **(P-3.5m)O-P** | 17.76 | -72 | 36.7 | 2.391 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **(P-2.5m)O-P** | 18.74 | -74 | 43.2 | 2.032 | NLOS |
| **(P-1.5m)O-P** | 19.73 | -72 | 40 | 2.194 | NLOS |
| **P** | 21.21 | -72 | 17.2 | 5.103 | NLOS |
| **(P-1.5m)P-Q** | 21.05 | -73 | 21.2 | 4.140 | NLOS |
| **(P-2.5m)P-Q** | 21.01 | -71 | 18.1 | 4.849 | NLOS |
| **(P-3.5m)P-Q** | 21.01 | -66 | 15 | 5.851 | NLOS |
| **Q** | 21.21 | -73 | 19.7 | 4.455 | NLOS |
| **(R-4.5m)Q-R** | 21.48 | -77 | 48.5 | 1.810 | NLOS |
| **(R-3.5m)Q-R** | 21.71 | -76 | 54.6 | 1.607 | NLOS |
| **(R-2.5m)Q-R** | 21.98 | -80 | 56.6 | 1.551 | NLOS |
| **(R-1.5m)Q-R** | 22.30 | -76 | 45 | 1.950 | NLOS |
| **R** | 22.85 | -79 | 50 | 1.755 | NLOS |
| **S** | 18.79 | -75 | 28.3 | 3.101 | NLOS |

Table B.3: Numerical results for AP at position “E-3M”.

## 4. Access Point at Position “J”

| **AP at J** | | **TX at J2 Position** | | **File Size: 10.9 MB** | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 23.00 | -57 | 8.8 | 9.973 | LOS |
| **(A-1.5m)A-B** | 23.05 | -66 | 10.1 | 8.690 | NLOS |
| **(A-2.5m)A-B** | 23.14 | -69 | 12 | 7.314 | NLOS |
| **(A-3.5m)A-B** | 23.26 | -72 | 11.9 | 7.375 | NLOS |
| **(A-4.5m)A-B** | 23.44 | -75 | 20.8 | 4.219 | NLOS |
| **B** | 23.77 | -81 | 21.7 | 4.044 | NLOS |
| **(C-5m)B-C** | 24.04 | -80 | 28.6 | 3.069 | NLOS |
| **(C-4m)B-C** | 24.35 | -82 | 44.7 | 1.963 | NLOS |
| **(C-3m)B-C** | 24.70 | -83 | 60.2 | 1.458 | NLOS |
| **(C-2m)B-C** | 25.08 | -83 | 26 | 3.376 | NLOS |
| **C** | 25.94 | -84 | 54.6 | 1.607 | NLOS |
| **(C-2m)C-D** | 24.19 | -84 | 39.4 | 2.228 | NLOS |
| **(C-3m)C-D** | 23.32 | -81 | 28.4 | 3.090 | NLOS |
| **(C-4m)C-D** | 22.47 | -87 | 157.7 | 0.557 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **(C-5m)C-D** | 21.63 | -83 | 46.8 | 1.875 | NLOS |
| **D** | 20.81 | -82 | 29.1 | 3.016 | NLOS |
| **(E-3m)D-E** | 19.21 | -78 | 19.6 | 4.478 | NLOS |
| **(E-2m)D-E** | 18.44 | -79 | 20.3 | 4.323 | NLOS |
| **E** | 16.97 | -70 | 10.1 | 8.690 | NLOS |
| **G** | 17.00 | -59 | 8.5 | 10.325 | LOS |
| **F** | 13.42 | -78 | 18.4 | 4.770 | NLOS |
| **(H-2.5m)F-H** | 12.26 | -68 | 10.3 | 8.521 | NLOS |
| **(H-1.5m)F-H** | 12.09 | -63 | 8.4 | 10.448 | NLOS |
| **H** | 12.00 | -61 | 8.6 | 10.205 | LOS |
| **I** | 6.00 | -56 | 8.4 | 10.448 | LOS |
| **L** | 10.82 | -61 | 11.3 | 7.767 | NLOS |
| **M** | 9.12 | -59 | 8.9 | 9.861 | NLOS |
| **K** | 6.00 | -48 | 8.4 | 10.448 | LOS |
| **N** | 12.00 | -59 | 9.9 | 8.865 | LOS |
| **(N-2m)N-O** | 12.17 | -61 | 8.6 | 10.205 | NLOS |
| **(N-3m)N-O** | 12.37 | -65 | 10.3 | 8.521 | NLOS |
| **O** | 12.82 | -67 | 12.4 | 7.078 | NLOS |
| **(P-2.5m)O-P** | 13.65 | -63 | 12.1 | 7.253 | NLOS |
| **(P-1.5m)O-P** | 14.15 | -64 | 11.3 | 7.767 | NLOS |
| **P** | 15.00 | -68 | 11.3 | 7.767 | NLOS |
| **(P-1.5m)P-Q** | 13.83 | -65 | 11 | 7.979 | NLOS |
| **(P-2.5m)P-Q** | 13.09 | -61 | 10.8 | 8.126 | NLOS |
| **Q** | 10.82 | -61 | 9.4 | 9.337 | NLOS |
| **(R-2.5m)Q-R** | 9.34 | -53 | 8.9 | 9.861 | NLOS |
| **(R-1.5m)Q-R** | 9.12 | -55 | 9.3 | 9.437 | NLOS |
| **R** | 9.00 | -45 | 8.4 | 10.448 | LOS |
| **S** | 4.50 | -41 | 8.1 | 10.835 | LOS |

Table B.4: Numerical results for AP at position “J”.

## 5. Access Point at Position “R”

| AP at R | | TX at R2 Position | | File Size: 10.9 MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 32.00 | -62 | 9.3 | 9.437 | LOS |
| **(A-1.5m)A-B** | 32.04 | -69 | 13.6 | 6.453 | NLOS |
| **(A-2.5m)A-B** | 32.10 | -79 | 18.7 | 4.693 | NLOS |
| **(A-3.5m)A-B** | 32.19 | -78 | 22.8 | 3.849 | NLOS |
| **(A-4.5m)A-B** | 32.31 | -74 | 12 | 7.314 | NLOS |
| **B** | 32.56 | -77 | 13.8 | 6.360 | NLOS |
| **(C-5m)B-C** | 32.76 | -83 | 56.9 | 1.542 | NLOS |
| **(C-4m)B-C** | 32.98 | -84 | 54.3 | 1.616 | NLOS |
| **(C-3m)B-C** | 33.24 | -87 | 92.6 | 0.948 | NLOS |
| **(C-2m)B-C** | 33.53 | -85 | 48.4 | 1.813 | NLOS |
| **C** | 34.18 | -87 | 82 | 1.070 | NLOS |
| **(C-2m)C-D** | 32.31 | -86 | 120 | 0.731 | NLOS |
| **(C-3m)C-D** | 31.38 | -83 | 71.3 | 1.231 | NLOS |
| **(C-4m)C-D** | 30.46 | -84 | 99.3 | 0.884 | NLOS |
| **(C-5m)C-D** | 29.55 | -84 | 87 | 1.009 | NLOS |
| **D** | 28.64 | -89 | 147.2 | 0.596 | NLOS |
| **(E-4m)D-E** | 27.73 | -80 | 45.6 | 1.925 | NLOS |
| **(E-3m)D-E** | 26.83 | -82 | 52.7 | 1.665 | NLOS |
| **(E-2m)D-E** | 25.94 | -77 | 34.3 | 2.559 | NLOS |
| **E** | 24.19 | -68 | 16.5 | 5.319 | NLOS |
| **G** | 26.00 | -59 | 9.1 | 9.645 | LOS |
| **H** | 21.00 | -55 | 8.8 | 9.973 | LOS |
| **(H-1.5m)H-F** | 21.05 | -66 | 10.8 | 8.126 | NLOS |
| **(H-2.5m)H-F** | 21.15 | -69 | 12 | 7.314 | NLOS |
| **(H-3.5m)H-F** | 21.29 | -71 | 15.5 | 5.662 | NLOS |
| **(H-4.5m)H-F** | 21.48 | -69 | 11.1 | 7.907 | NLOS |
| **F** | 21.84 | -78 | 22.6 | 3.883 | NLOS |
| **I** | 15.00 | -51 | 8.6 | 10.205 | LOS |
| **L** | 17.49 | -70 | 13.5 | 6.501 | NLOS |
| **M** | 13.83 | -71 | 12 | 7.314 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **J** | 9.00 | -44 | 8.2 | 10.703 | LOS |
| **(J-1.5m)J-K** | 9.12 | -53 | 9.2 | 9.540 | NLOS |
| **(J-2.5m)J-K** | 9.34 | -55 | 9.3 | 9.437 | NLOS |
| **(J-3.5m)J-K** | 9.66 | -60 | 10.2 | 8.604 | NLOS |
| **K** | 10.82 | -61 | 10.9 | 8.052 | NLOS |
| **(N-2.5m)K-N** | 13.09 | -68 | 12.1 | 7.253 | NLOS |
| **(N-1.5m)K-N** | 13.83 | -64 | 11.2 | 7.836 | NLOS |
| **N** | 15.00 | -65 | 11.1 | 7.907 | NLOS |
| **(N-2m)N-O** | 13.89 | -61 | 9.2 | 9.540 | NLOS |
| **(N-3m)N-O** | 13.42 | -62 | 10.3 | 8.521 | NLOS |
| **O** | 12.82 | -66 | 12 | 7.314 | LOS |
| **(P-3.5m)O-P** | 12.50 | -61 | 10.5 | 8.359 | NLOS |
| **(P-2.5m)O-P** | 12.26 | -56 | 9.4 | 9.337 | NLOS |
| **(P-1.5m)O-P** | 12.09 | -54 | 9.6 | 9.142 | NLOS |
| **P** | 12.00 | -51 | 8.6 | 10.205 | LOS |
| **Q** | 6.00 | -49 | 8.2 | 10.703 | LOS |
| **S** | 4.50 | -46 | 8.4 | 10.448 | LOS |

Table B.5: Numerical results for AP at position “R”.

## 6. Access Point at Position “N-3M”

| **AP at “N-3m”** | | **TX at N2 Position** | | **File Size: 10.9 MB** | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 24.70 | -83 | 104.6 | 0.839 | NLOS |
| **(A-1.5m)A-B** | 24.19 | -84 | 96.8 | 0.907 | NLOS |
| **(A-2.5m)A-B** | 23.90 | -79 | 53.4 | 1.644 | NLOS |
| **(A-3.5m)A-B** | 23.65 | -84 | 116.7 | 0.752 | NLOS |
| **(A-4.5m)A-B** | 23.44 | -79 | 78.4 | 1.119 | NLOS |
| **B** | 23.19 | -81 | 97.6 | 0.899 | NLOS |
| **(C-5m)B-C** | 23.02 | -75 | 46.8 | 1.875 | NLOS |
| **(C-4m)B-C** | 23.00 | -83 | 82.5 | 1.064 | NLOS |
| **(C-3m)B-C** | 23.02 | -82 | 68.2 | 1.287 | NLOS |
| **(C-2m)B-C** | 23.09 | -81 | 76.7 | 1.144 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **C** | 23.19 | -77 | 46.1 | 1.904 | NLOS |
| **(C-2m)C-D** | 21.21 | -79 | 43.2 | 2.032 | NLOS |
| **(C-3m)C-D** | 20.22 | -76 | 31.4 | 2.795 | NLOS |
| **(C-4m)C-D** | 19.24 | -72 | 28.3 | 3.101 | NLOS |
| **D** | 17.26 | -70 | 13.2 | 6.649 | NLOS |
| **(E-2m)D-E** | 14.32 | -64 | 12.3 | 7.135 | NLOS |
| **E** | 12.37 | -60 | 11.2 | 7.836 | NLOS |
| **F** | 12.37 | -55 | 10.5 | 8.359 | NLOS |
| **(A-2m)A-G** | 22.85 | -78 | 51.7 | 1.698 | NLOS |
| **(A-3m)A-G** | 21.93 | -76 | 24.6 | 3.568 | NLOS |
| **(A-4m)A-G** | 21.02 | -77 | 19.1 | 4.595 | NLOS |
| **(A-5m)A-G** | 20.12 | -75 | 18.2 | 4.822 | NLOS |
| **G** | 19.24 | -76 | 20.6 | 4.260 | NLOS |
| **(H-2m)G-H** | 16.64 | -78 | 21.6 | 4.063 | NLOS |
| **H** | 15.00 | -72 | 15.6 | 5.626 | NLOS |
| **I** | 10.82 | -76 | 14.1 | 6.224 | NLOS |
| **L** | 6.00 | -51 | 8.8 | 9.973 | LOS |
| **M** | 1.50 | -43 | 8.2 | 10.703 | LOS |
| **J** | 9.00 | -55 | 8.7 | 10.008 | LOS |
| **K** | 3.00 | -48 | 8.1 | 10.835 | LOS |
| **N** | 3.00 | -44 | 8.2 | 10.703 | LOS |
| **(N-2m)N-O** | 3.61 | -52 | 8.3 | 10.574 | NLOS |
| **(N-3m)N-O** | 4.24 | -54 | 8.5 | 10.325 | NLOS |
| **O** | 5.41 | -52 | 8.3 | 10.574 | NLOS |
| **P** | 9.49 | -55 | 8.2 | 10.703 | NLOS |
| **(P-1.5m)P-Q** | 9.12 | -56 | 8.2 | 10.703 | NLOS |
| **(P-2.5m)P-Q** | 9.01 | -62 | 9.2 | 9.540 | NLOS |
| **(P-3.5m)P-Q** | 9.01 | -55 | 8.5 | 10.325 | NLOS |
| **Q** | 9.49 | -61 | 8.2 | 10.703 | NLOS |
| **(R-4.5m)Q-R** | 10.06 | -69 | 9.9 | 8.865 | NLOS |
| **(R-3.5m)Q-R** | 10.55 | -64 | 8.5 | 10.325 | NLOS |
| **(R-2.5m)Q-R** | 11.10 | -68 | 8.9 | 9.861 | NLOS |
| **(R-1.5m)Q-R** | 11.72 | -63 | 8.3 | 10.574 | NLOS |
| **R** | 12.73 | -62 | 8.4 | 10.448 | NLOS |
| **S** | 10.06 | -59 | 8.5 | 10.325 | NLOS |

Table B.6: Numerical results for AP at position “N-3M”.

## 7. Access Point at Position “H”

| AP at H | | TX at H2 Position | | File Size: 10.9MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 11.00 | -59 | 8.4 | 10.448 | LOS |
| **(A-1.5m)A-B** | 11.10 | -65 | 11.3 | 7.767 | NLOS |
| **(A-2.5m)A-B** | 11.28 | -64 | 10.2 | 8.604 | NLOS |
| **(A-3.5m)A-B** | 11.54 | -69 | 12.2 | 7.194 | NLOS |
| **B** | 12.53 | -69 | 11.9 | 7.375 | NLOS |
| **(C-3m)B-C** | 14.21 | -64 | 10.4 | 8.439 | NLOS |
| **(C-2m)B-C** | 14.87 | -66 | 10.7 | 8.202 | NLOS |
| **C** | 16.28 | -79 | 32.6 | 2.692 | NLOS |
| **(C-2m)C-D** | 15.00 | -74 | 23.6 | 3.719 | NLOS |
| **(C-3m)C-D** | 14.42 | -71 | 22.8 | 3.849 | NLOS |
| **D** | 13.00 | -70 | 21.7 | 4.044 | NLOS |
| **(E-3m)D-E** | 12.37 | -65 | 13.6 | 6.453 | NLOS |
| **(E-2m)D-E** | 12.17 | -64 | 9.1 | 9.645 | NLOS |
| **E** | 12.00 | -63 | 8.9 | 9.861 | LOS |
| **F** | 6.00 | -54 | 8.3 | 10.574 | LOS |
| **G** | 5.00 | -54 | 8.5 | 10.325 | LOS |
| **I** | 6.00 | -56 | 9.3 | 9.437 | LOS |
| **L** | 10.82 | -68 | 10.4 | 8.439 | NLOS |
| **M** | 13.83 | -69 | 11.8 | 7.438 | NLOS |
| **J** | 12.00 | -55 | 9.8 | 8.956 | LOS |
| **(J-1.5m)J-K** | 12.09 | -66 | 10.5 | 8.359 | NLOS |
| **(J-2.5m)J-K** | 12.26 | -68 | 11.7 | 7.501 | NLOS |
| **K** | 13.42 | -73 | 15.4 | 5.699 | NLOS |
| **N** | 16.97 | -74 | 13.3 | 6.599 | NLOS |
| **(N-2m)N-O** | 18.44 | -80 | 31.7 | 2.769 | NLOS |
| **(N-3m)N-O** | 19.21 | -81 | 32.9 | 2.668 | NLOS |
| **(N-4m)N-O** | 20.00 | -80 | 62.3 | 1.409 | NLOS |
| **O** | 20.40 | -84 | 101.9 | 0.861 | NLOS |
| **(P-3.5m)O-P** | 21.22 | -84 | 97.2 | 0.903 | NLOS |
| **(P-2.5m)O-P** | 22.05 | -82 | 133.9 | 0.655 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **(P-1.5m)O-P** | 22.90 | -83 | 123 | 0.714 | NLOS |
| **P** | 24.19 | -80 | 51 | 1.721 | NLOS |
| **(P-1.5m)P-Q** | 23.48 | -82 | 68.2 | 1.287 | NLOS |
| **(P-2.5m)P-Q** | 23.05 | -81 | 66.8 | 1.314 | NLOS |
| **(P-3.5m)P-Q** | 22.66 | -80 | 55.3 | 1.587 | NLOS |
| **Q** | 21.84 | -84 | 44.8 | 1.959 | NLOS |
| **(R-4.5m)Q-R** | 21.48 | -76 | 34.7 | 2.529 | NLOS |
| **(R-3.5m)Q-R** | 21.29 | -70 | 23.2 | 3.783 | NLOS |
| **(R-2.5m)Q-R** | 21.15 | -64 | 15.6 | 5.626 | NLOS |
| **(R-1.5m)Q-R** | 21.05 | -67 | 17.4 | 5.044 | NLOS |
| **R** | 21.00 | -59 | 16.8 | 5.224 | LOS |
| **S** | 16.50 | -54 | 13.7 | 6.406 | LOS |

Table B.7: Numerical results for AP at position “H”.

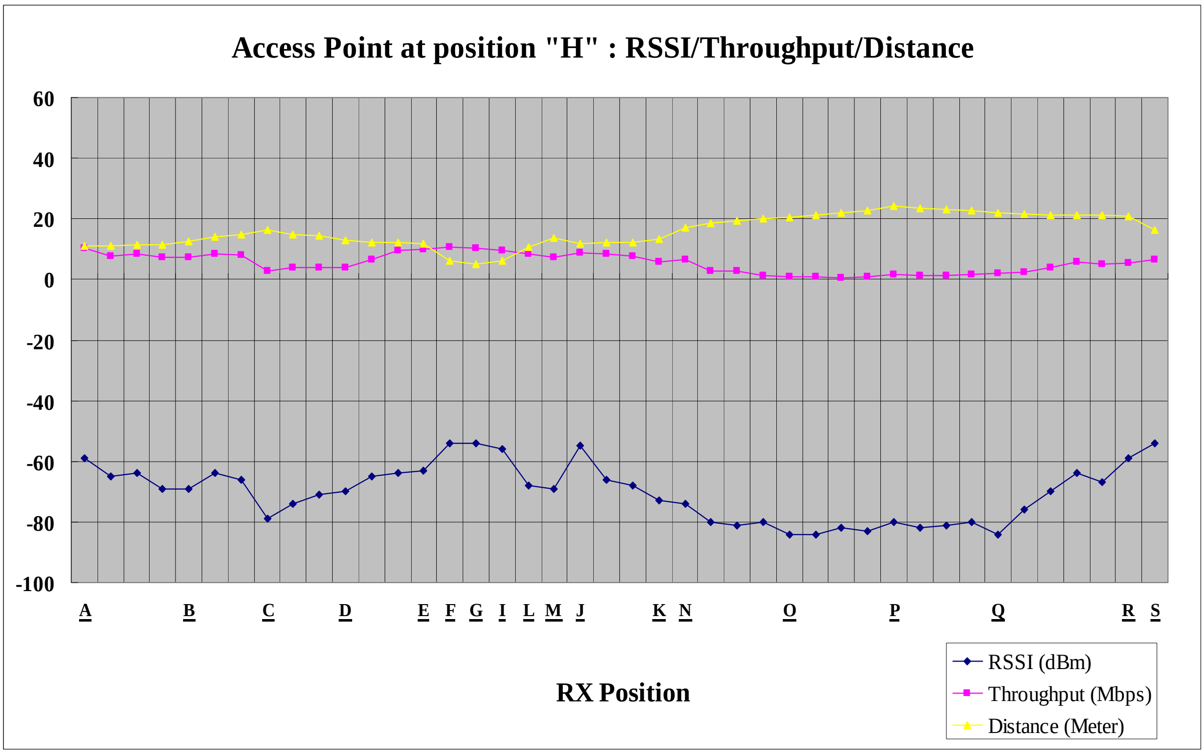


Figure B.1: Throughput/RSSI/Distance for AP at position “H”.

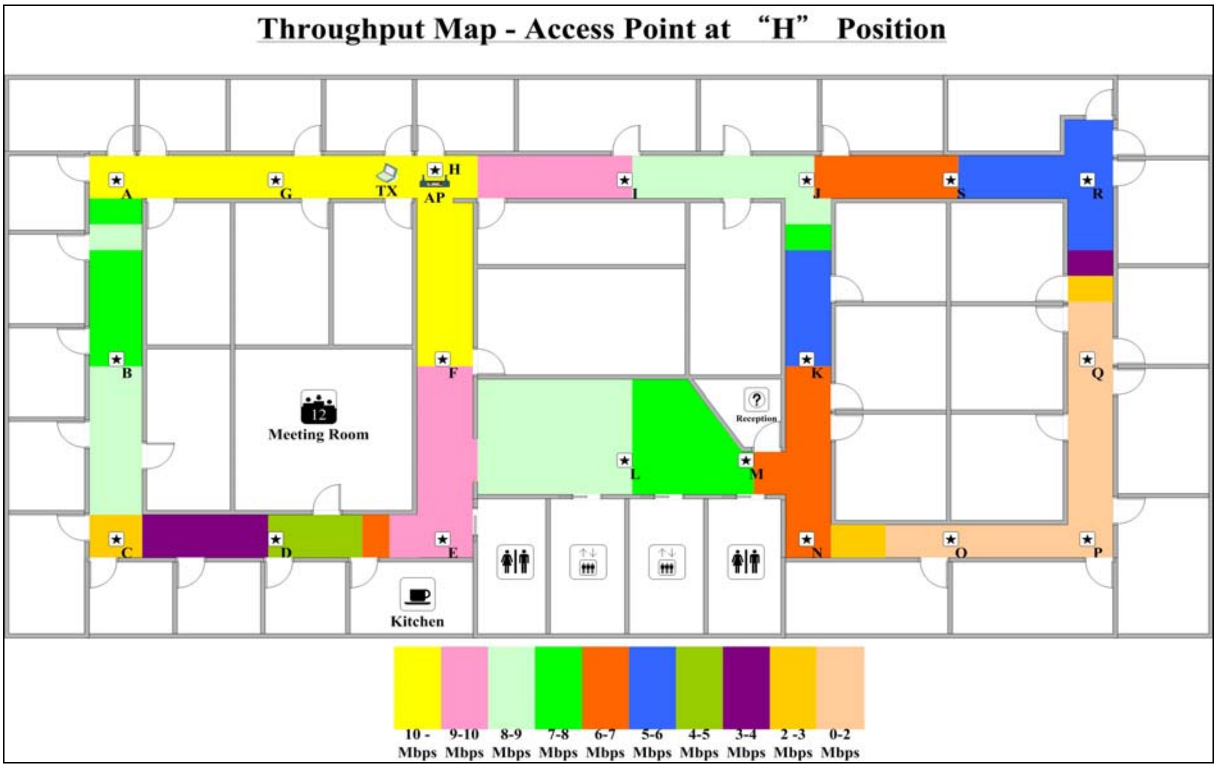


Figure B.2: Throughput map for AP at position "H".

## 8. Access Point at Position "F"

| AP at F | | TX at F2 Position | | File Size: 10.9 MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 12.53 | -68 | 12.9 | 6.803 | NLOS |
| **(A-1.5m)A-B** | 11.88 | -73 | 19.3 | 4.547 | NLOS |
| **(A-2.5m)A-B** | 11.54 | -74 | 20.4 | 4.302 | NLOS |
| **B** | 11.00 | -66 | 14.3 | 6.137 | NLOS |
| **(C-3m)B-C** | 11.40 | -69 | 15.6 | 5.626 | NLOS |
| **(C-2m)B-C** | 11.70 | -73 | 11.6 | 7.566 | NLOS |
| **C** | 12.53 | -73 | 20 | 4.388 | NLOS |
| **(C-2m)C-D** | 10.82 | -67 | 13 | 6.751 | NLOS |
| **(C-3m)C-D** | 10.00 | -64 | 11.2 | 7.836 | NLOS |
| **D** | 7.81 | -66 | 10.5 | 8.359 | NLOS |
| **(E-3m)D-E** | 6.71 | -62 | 10.8 | 8.126 | NLOS |
| **(E-2m)D-E** | 6.32 | -60 | 11.5 | 7.632 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **E** | 6.00 | -56 | 9.5 | 9.238 | LOS |
| **G** | 7.81 | -64 | 10.9 | 8.052 | NLOS |
| **H** | 6.00 | -50 | 8.8 | 9.973 | LOS |
| **I** | 8.49 | -70 | 10.3 | 8.521 | NLOS |
| **L** | 6.71 | -57 | 9.4 | 9.337 | NLOS |
| **M** | 10.92 | -66 | 10.5 | 8.359 | NLOS |
| **J** | 13.42 | -71 | 14.1 | 6.224 | NLOS |
| **(J-1.5m)J-K** | 12.82 | -73 | 14.5 | 6.053 | NLOS |
| **(J-2.5m)J-K** | 12.50 | -76 | 16.2 | 5.418 | NLOS |
| **K** | 12.00 | -75 | 18.6 | 4.719 | NLOS |
| **(N-2.5m)K-N** | 12.26 | -66 | 13.4 | 6.550 | NLOS |
| **(N-1.5m)K-N** | 12.09 | -70 | 16.5 | 5.319 | NLOS |
| **N** | 13.42 | -74 | 19.6 | 4.478 | NLOS |
| **(N-2m)N-O** | 15.23 | -78 | 29.2 | 3.006 | NLOS |
| **(N-3m)N-O** | 16.16 | -76 | 23.6 | 3.719 | NLOS |
| **O** | 17.56 | -78 | 28.1 | 3.123 | NLOS |
| **(P-3.5m)O-P** | 18.50 | -83 | 48.8 | 1.798 | NLOS |
| **(P-2.5m)O-P** | 19.45 | -82 | 69.2 | 1.268 | NLOS |
| **(P-1.5m)O-P** | 20.40 | -84 | 118.5 | 0.741 | NLOS |
| **P** | 21.84 | -77 | 28.8 | 3.047 | NLOS |
| **(P-1.5m)P-Q** | 21.48 | -80 | 43.6 | 2.013 | NLOS |
| **(P-2.5m)P-Q** | 21.29 | -81 | 52.1 | 1.685 | NLOS |
| **(P-3.5m)P-Q** | 21.15 | -83 | 51.1 | 1.718 | NLOS |
| **Q** | 21.00 | -84 | 67.8 | 1.294 | NLOS |
| **(R-3.5m)Q-R** | 21.15 | -84 | 74.5 | 1.178 | NLOS |
| **(R-2.5m)Q-R** | 21.29 | -85 | 67 | 1.310 | NLOS |
| **(R-1.5m)Q-R** | 21.48 | -88 | 142.1 | 0.618 | NLOS |
| **R** | 21.84 | -83 | 63.8 | 1.376 | NLOS |
| **S** | 17.56 | -76 | 28.3 | 3.101 | NLOS |

Table B.8: Numerical results for AP at position “F”.

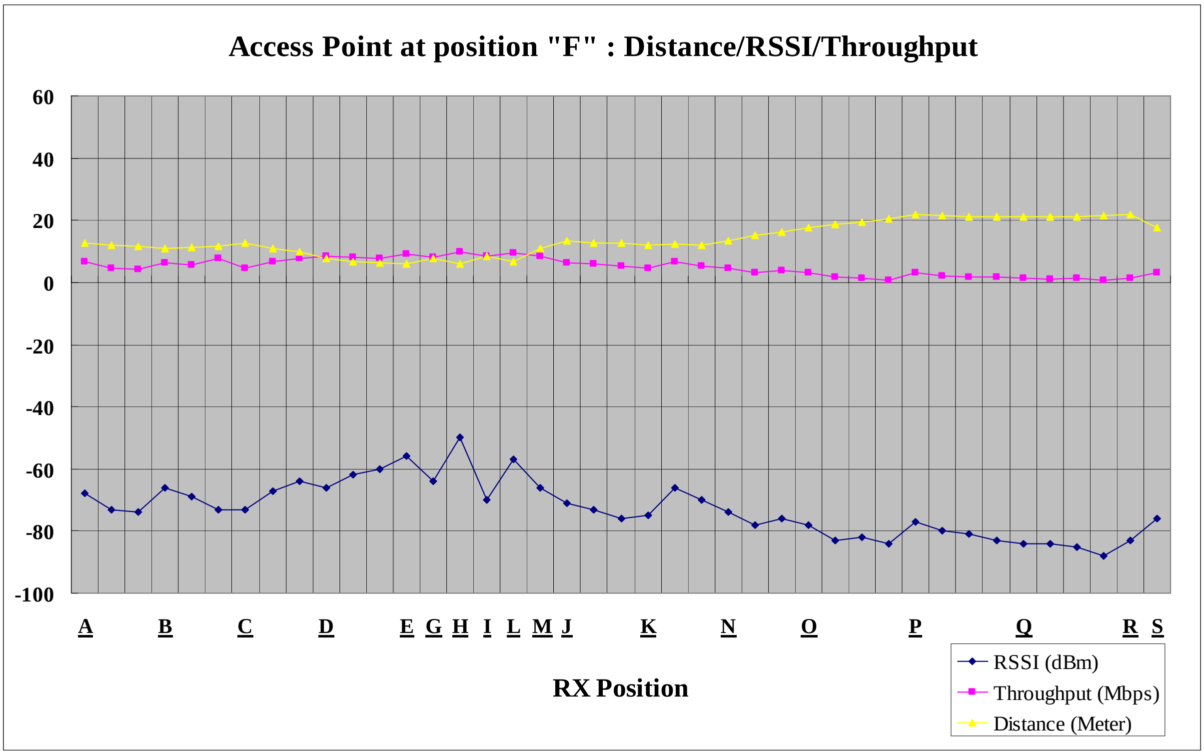


Figure B.3: Throughput/RSSI/Distance for AP at position “F”.

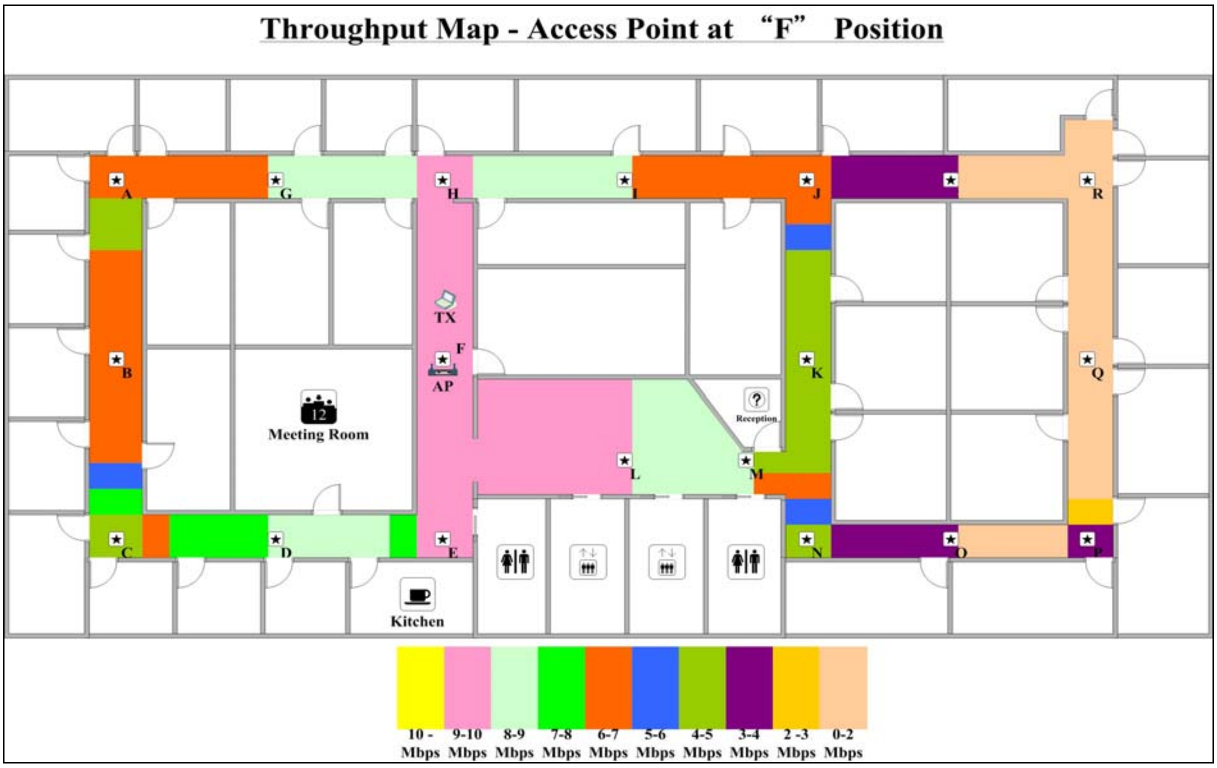


Figure B.4: Throughput map for AP at position “F”.

## 9. Access Point at Position "I"

| AP at I | | TX at I2 Position | | File Size: 10.9 MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 17.00 | -60 | 9.3 | 9.437 | LOS |
| **(A-1.5m)A-B** | 17.07 | -62 | 9.2 | 9.540 | NLOS |
| **(A-2.5m)A-B** | 17.18 | -63 | 9.6 | 9.142 | NLOS |
| **B** | 18.03 | -71 | 11.4 | 7.699 | NLOS |
| **(C-4m)B-C** | 18.79 | -76 | 24.4 | 3.597 | NLOS |
| **(C-3m)B-C** | 19.24 | -74 | 17.1 | 5.132 | NLOS |
| **(C-2m)B-C** | 19.72 | -75 | 21.7 | 4.044 | NLOS |
| **C** | 20.81 | -73 | 14.2 | 6.181 | NLOS |
| **(C-2m)C-D** | 19.21 | -76 | 25.9 | 3.389 | NLOS |
| **(C-3m)C-D** | 18.44 | -74 | 20.4 | 4.302 | NLOS |
| **(C-4m)C-D** | 17.69 | -75 | 20.8 | 4.219 | NLOS |
| **D** | 16.28 | -74 | 19.4 | 4.524 | NLOS |
| **(E-3m)D-E** | 15.00 | -72 | 19.8 | 4.433 | NLOS |
| **(E-2m)D-E** | 14.42 | -73 | 18.3 | 4.796 | NLOS |
| **E** | 13.42 | -68 | 9.9 | 8.865 | NLOS |
| **G** | 11.00 | -60 | 8.4 | 10.448 | LOS |
| **F** | 8.49 | -66 | 10.7 | 8.202 | NLOS |
| **(H-2.5m)F-H** | 6.50 | -62 | 9.8 | 8.956 | NLOS |
| **(H-1.5m)F-H** | 6.18 | -59 | 8.6 | 10.205 | NLOS |
| **H** | 6.00 | -49 | 8.3 | 10.574 | LOS |
| **L** | 9.00 | -68 | 9.2 | 9.540 | NLOS |
| **M** | 10.06 | -61 | 8.4 | 10.448 | NLOS |
| **J** | 6.00 | -56 | 8.6 | 10.205 | LOS |
| **(J-1.5m)J-K** | 6.18 | -53 | 8.3 | 10.574 | NLOS |
| **(J-2.5m)J-K** | 6.50 | -59 | 9.7 | 9.048 | NLOS |
| **K** | 8.49 | -66 | 12.2 | 7.194 | NLOS |
| **(N-2.5m)K-N** | 11.24 | -59 | 10.8 | 8.126 | NLOS |
| **(N-1.5m)K-N** | 12.09 | -64 | 13.7 | 6.406 | NLOS |
| **N** | 13.42 | -75 | 20.5 | 4.281 | NLOS |
| **(N-2m)N-O** | 14.42 | -73 | 15.2 | 5.774 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **(N-3m)N-O** | 15.00 | -72 | 15.6 | 5.626 | NLOS |
| **O** | 15.95 | -74 | 20.5 | 4.281 | NLOS |
| **(P-3.5m)O-P** | 16.62 | -77 | 22.3 | 3.936 | NLOS |
| **(P-2.5m)O-P** | 17.33 | -83 | 47.8 | 1.836 | NLOS |
| **(P-1.5m)O-P** | 18.06 | -80 | 32 | 2.743 | NLOS |
| **P** | 19.21 | -76 | 24.3 | 3.612 | NLOS |
| **(P-1.5m)P-Q** | 18.31 | -77 | 21.1 | 4.159 | NLOS |
| **(P-2.5m)P-Q** | 17.76 | -71 | 13.2 | 6.649 | NLOS |
| **(P-3.5m)P-Q** | 17.24 | -72 | 13.2 | 6.649 | NLOS |
| **Q** | 16.16 | -70 | 14.2 | 6.181 | NLOS |
| **(R-2.5m)Q-R** | 15.21 | -62 | 10.6 | 8.280 | NLOS |
| **(R-1.5m)Q-R** | 15.07 | -62 | 8.8 | 9.973 | NLOS |
| **R** | 15.00 | -48 | 8.3 | 10.574 | LOS |
| **S** | 10.50 | -52 | 8.5 | 10.325 | LOS |

Table B.9: Numerical results for AP at position "I".

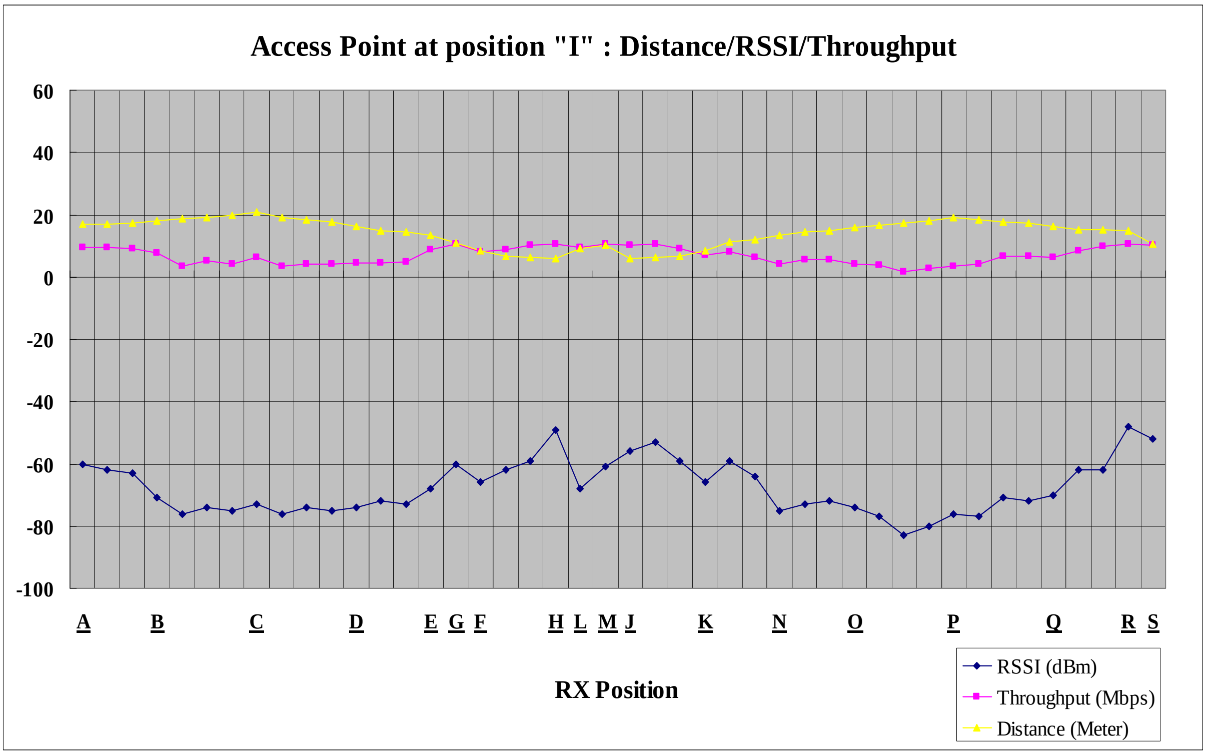


Figure B.5: Throughput/RSSI/Distance for AP at position "I".

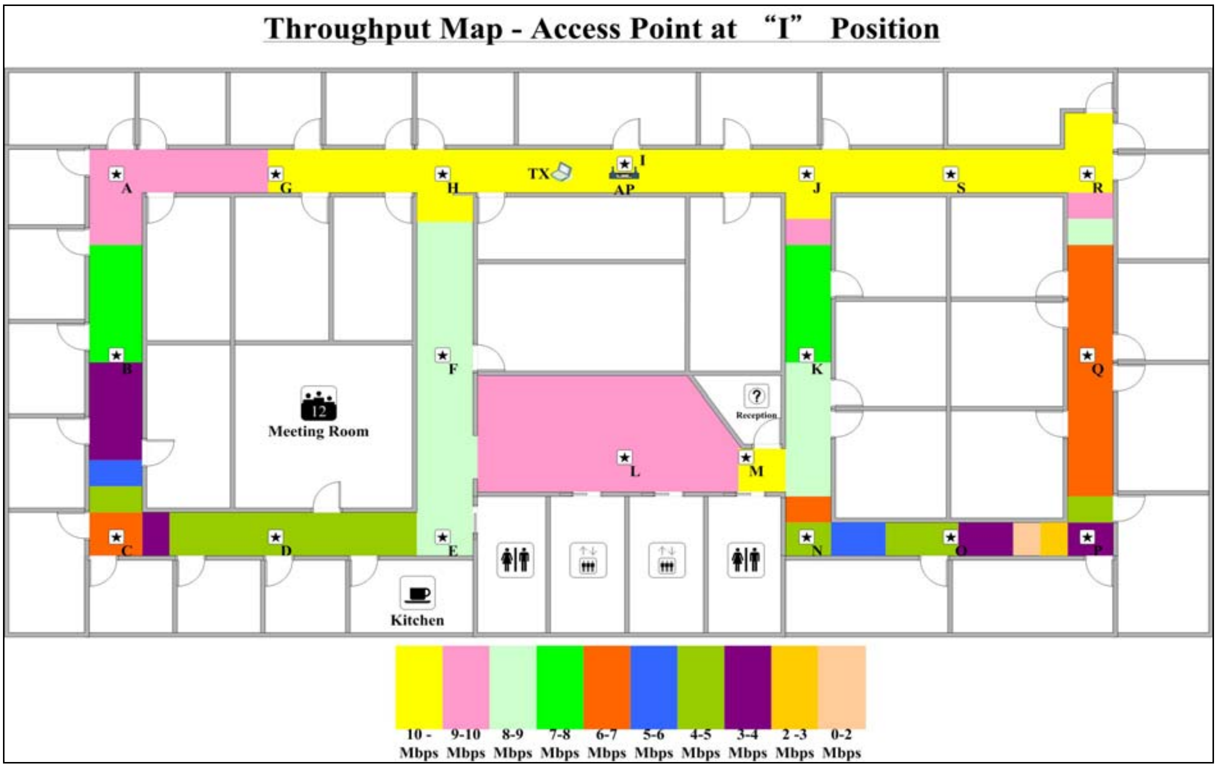


Figure B.6: Throughput map for AP at position "I".

## 10. Access Point at Position "L"

| AP at L Position | | TX at L2 Position | | File Size: 10.9 MB | |
|---|---|---|---|---|---|
| RX Position | Distance from AP (Meter) | Signal Strength (dBm) | Time (second) | Throughput (Mbps) | LOS/NLOS |
| A | 19.24 | -78 | 21.1 | 4.159 | NLOS |
| (A-1.5m)A-B | 18.58 | -77 | 20.7 | 4.240 | NLOS |
| (A-2.5m)A-B | 18.20 | -78 | 23.2 | 3.783 | NLOS |
| (A-3.5m)A-B | 17.87 | -76 | 21.3 | 4.120 | NLOS |
| (A-4.5m)A-B | 17.59 | -77 | 23.3 | 3.767 | NLOS |
| B | 17.26 | -79 | 24.9 | 3.525 | NLOS |
| (C-5m)B-C | 17.12 | -74 | 14.9 | 5.890 | NLOS |
| (C-4m)B-C | 17.03 | -75 | 20.2 | 4.345 | NLOS |
| (C-3m)B-C | 17.00 | -78 | 27.6 | 3.180 | NLOS |
| (C-2m)B-C | 17.03 | -76 | 13.9 | 6.314 | NLOS |
| C | 17.26 | -73 | 13.2 | 6.649 | NLOS |
| (C-2m)C-D | 15.30 | -72 | 10.6 | 8.280 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **(C-3m)C-D** | 14.32 | -74 | 13.6 | 6.453 | NLOS |
| **(C-4m)C-D** | 13.34 | -70 | 12.2 | 7.194 | NLOS |
| **D** | 11.40 | -71 | 10.4 | 8.439 | NLOS |
| **(E-3m)D-E** | 9.49 | -68 | 9.1 | 9.645 | NLOS |
| **(E-2m)D-E** | 8.54 | -68 | 9.5 | 9.238 | NLOS |
| **E** | 6.71 | -47 | 8.1 | 10.835 | NLOS |
| **(A-2m)A-G** | 17.49 | -73 | 22.6 | 3.883 | NLOS |
| **(A-3m)A-G** | 16.64 | -76 | 25 | 3.511 | NLOS |
| **(A-4m)A-G** | 15.81 | -77 | 27.8 | 3.157 | NLOS |
| **G** | 14.21 | -69 | 18 | 4.876 | NLOS |
| **F** | 6.71 | -56 | 8.3 | 10.574 | NLOS |
| **(H-2.5m)F-H** | 8.85 | -63 | 14.7 | 5.970 | NLOS |
| **(H-1.5m)F-H** | 9.60 | -72 | 21.7 | 4.044 | NLOS |
| **H** | 10.82 | -60 | 8.3 | 10.574 | NLOS |
| **I** | 9.00 | -65 | 9.4 | 9.337 | NLOS |
| **M** | 4.50 | -43 | 8.1 | 10.835 | LOS |
| **J** | 10.82 | -65 | 9.6 | 9.142 | NLOS |
| **K** | 6.71 | -57 | 8.3 | 10.574 | NLOS |
| **(N-2.5m)K-N** | 6.08 | -56 | 8.2 | 10.703 | NLOS |
| **(N-1.5m)K-N** | 6.32 | -62 | 8.5 | 10.325 | NLOS |
| **N** | 6.71 | -59 | 8.6 | 10.205 | NLOS |
| **(N-2m)N-O** | 8.54 | -69 | 8.9 | 9.861 | NLOS |
| **(N-3m)N-O** | 9.49 | -67 | 9.7 | 9.048 | NLOS |
| **O** | 10.92 | -68 | 9.5 | 9.238 | NLOS |
| **(P-3.5m)O-P** | 11.88 | -68 | 9.5 | 9.238 | NLOS |
| **(P-2.5m)O-P** | 12.85 | -66 | 9.6 | 9.142 | NLOS |
| **(P-1.5m)O-P** | 13.83 | -71 | 10.5 | 8.359 | NLOS |
| **P** | 15.30 | -72 | 11 | 7.979 | NLOS |
| **(P-1.5m)P-Q** | 15.07 | -62 | 12 | 7.314 | NLOS |
| **(P-2.5m)P-Q** | 15.01 | -64 | 8.3 | 10.574 | NLOS |
| **(P-3.5m)P-Q** | 15.01 | -67 | 9.7 | 9.048 | NLOS |
| **(P-4.5m)P-Q** | 15.07 | -66 | 9 | 9.752 | NLOS |
| **Q** | 15.30 | -70 | 12.7 | 6.911 | NLOS |
| **(R-4.5m)Q-R** | 15.66 | -67 | 13.6 | 6.453 | NLOS |
| **(R-3.5m)Q-R** | 15.98 | -74 | 22.5 | 3.901 | NLOS |
| **(R-2.5m)Q-R** | 16.35 | -76 | 27.8 | 3.157 | NLOS |
| **(R-1.5m)Q-R** | 16.77 | -75 | 22.5 | 3.901 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **R** | 17.49 | -77 | 31 | 2.831 | NLOS |
| **(R-1.5m)S-R** | 16.22 | -78 | 30.9 | 2.840 | NLOS |
| **(R-2.5m)R-S** | 15.40 | -77 | 26.1 | 3.363 | NLOS |
| **(R-3.5m)R-S** | 14.60 | -73 | 15.4 | 5.699 | NLOS |
| **S** | 13.83 | -68 | 10.3 | 8.521 | NLOS |

Table B.10: Numerical results for AP at position “L”.

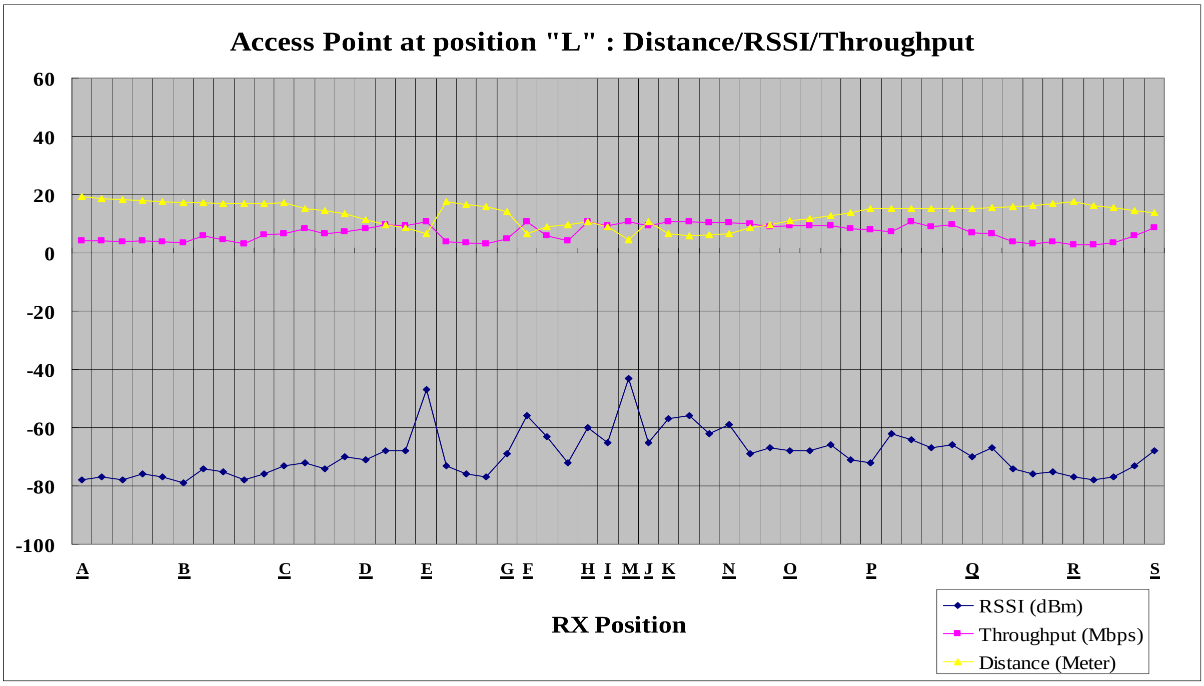


Figure B.7: Throughput/RSSI/Distance for AP at position “L”.

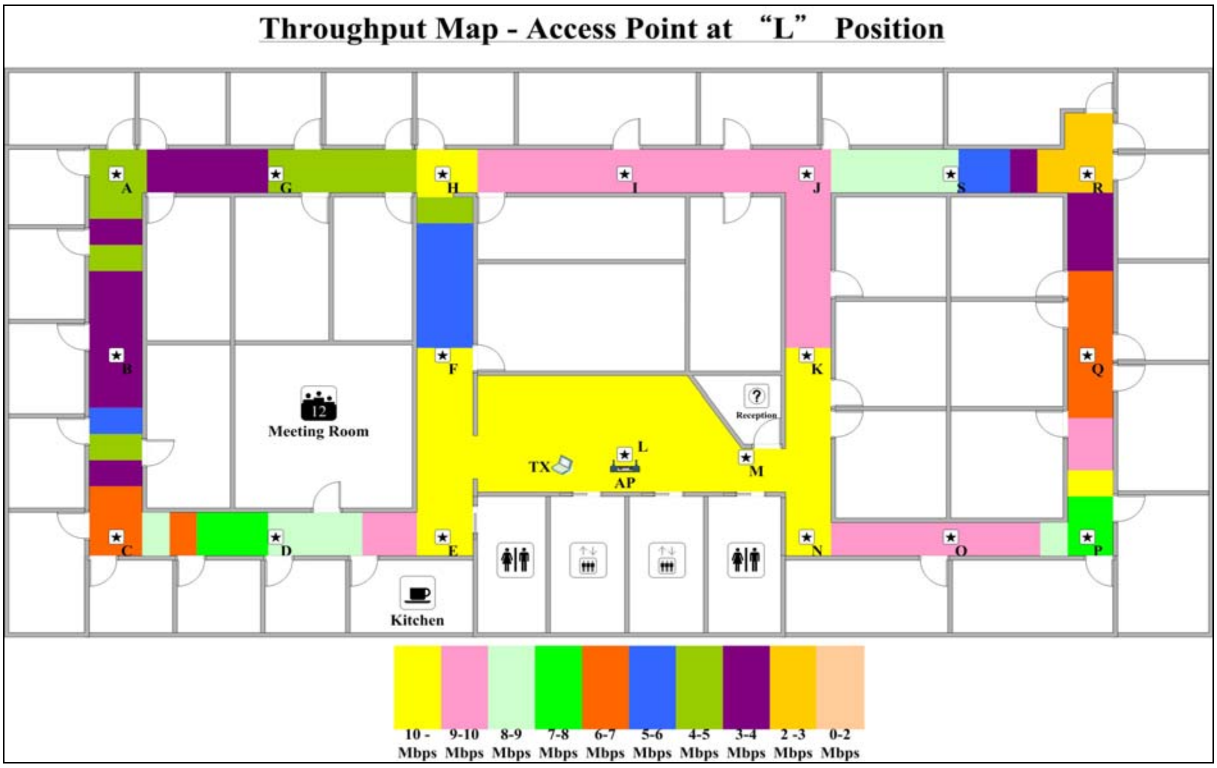


Figure B.8: Throughput map for AP at position "L".

## 11. Access Point at Position "K"

| AP at K Position | | TX at K2 Position | | File Size: 10.9 MB | |
|---|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (second)** | **Throughput (Mbps)** | **LOS/NLOS** |
| **A** | 23.77 | -80 | 83.4 | 1.052 | NLOS |
| **(A-1.5m)A-B** | 23.44 | -84 | 97.3 | 0.902 | NLOS |
| **(A-2.5m)A-B** | 23.26 | -89 | 136.4 | 0.643 | NLOS |
| **(A-3.5m)A-B** | 23.14 | -82 | 73.2 | 1.199 | NLOS |
| **B** | 23.00 | -86 | 106.7 | 0.823 | NLOS |
| **(C-4m)B-C** | 23.09 | -82 | 102.5 | 0.856 | NLOS |
| **(C-3m)B-C** | 23.19 | -85 | 114.6 | 0.766 | NLOS |
| **(C-2m)B-C** | 23.35 | -80 | 94.8 | 0.926 | NLOS |
| **C** | 23.77 | -79 | 63.4 | 1.384 | NLOS |
| **(C-2m)C-D** | 21.84 | -78 | 57.3 | 1.532 | NLOS |
| **(C-3m)C-D** | 20.88 | -83 | 79.8 | 1.100 | NLOS |
| **(C-4m)C-D** | 19.92 | -80 | 48.4 | 1.813 | NLOS |

| | | | | | |
|---|---|---|---|---|---|
| **D** | 18.03 | -76 | 36.1 | 2.431 | NLOS |
| **(E-4m)D-E** | 17.09 | -72 | 33.7 | 2.604 | NLOS |
| **(E-3m)D-E** | 16.16 | -73 | 26.5 | 3.312 | NLOS |
| **(E-2m)D-E** | 15.23 | -68 | 24.6 | 3.568 | NLOS |
| **E** | 13.42 | -63 | 19.6 | 4.478 | NLOS |
| **F** | 12.00 | -70 | 18.2 | 4.822 | NLOS |
| **G** | 18.03 | -78 | 45.1 | 1.946 | NLOS |
| **H** | 13.42 | -73 | 31.2 | 2.813 | NLOS |
| **(H-1.5m)F-H** | 12.82 | -72 | 26.8 | 3.275 | NLOS |
| **(H-2.5m)F-H** | 12.50 | -72 | 24.9 | 3.525 | NLOS |
| **I** | 8.49 | -67 | 11.2 | 7.836 | NLOS |
| **L** | 6.71 | -52 | 9.2 | 9.540 | NLOS |
| **M** | 3.35 | -54 | 8.9 | 9.861 | NLOS |
| **J** | 6.00 | -48 | 8.3 | 10.574 | LOS |
| **N** | 6.00 | -46 | 8.4 | 10.448 | LOS |
| **(N-2m)N-O** | 6.32 | -61 | 9.7 | 9.048 | NLOS |
| **(N-3m)N-O** | 6.71 | -66 | 11.2 | 7.836 | NLOS |
| **O** | 7.50 | -72 | 12.4 | 7.078 | NLOS |
| **(P-2.5m)O-P** | 8.85 | -71 | 12.8 | 6.857 | NLOS |
| **(P-1.5m)O-P** | 9.60 | -65 | 13.3 | 6.599 | NLOS |
| **P** | 10.82 | -68 | 15.2 | 5.774 | NLOS |
| **(P-1.5m)P-Q** | 10.06 | -74 | 23.2 | 3.783 | NLOS |
| **(P-2.5m)P-Q** | 9.66 | -71 | 18.8 | 4.668 | NLOS |
| **Q** | 9.00 | -70 | 15 | 5.851 | NLOS |
| **(R-2.5m)Q-R** | 9.66 | -74 | 16.1 | 5.451 | NLOS |
| **(R-1.5m)Q-R** | 10.06 | -76 | 21.4 | 4.101 | NLOS |
| **R** | 10.82 | -67 | 11.6 | 7.566 | NLOS |
| **(R-1.5m)R-S** | 9.60 | -65 | 11.2 | 7.836 | NLOS |
| **(R-2.5m)R-S** | 8.85 | -66 | 10.3 | 8.521 | NLOS |
| **S** | 7.50 | -61 | 9.7 | 9.048 | NLOS |

Table B.11: Numerical results for AP at position “K”.

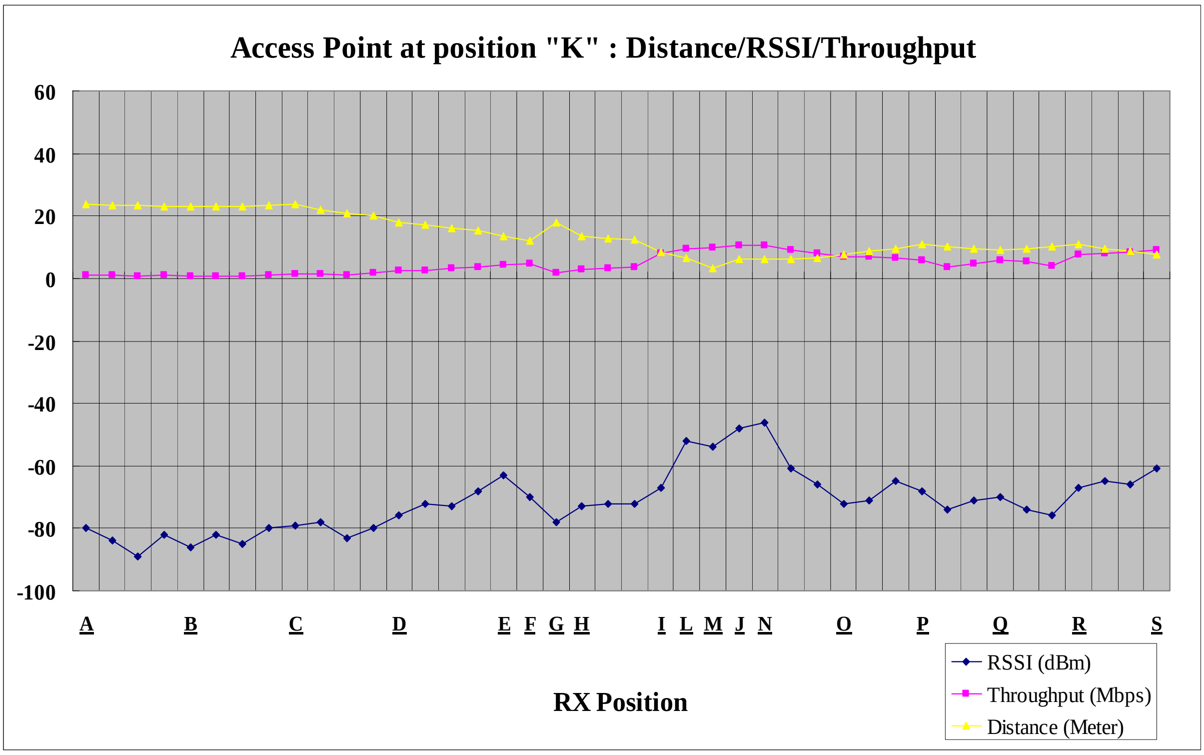


Figure B.9: Throughput/RSSI/Distance for AP at position “K”.

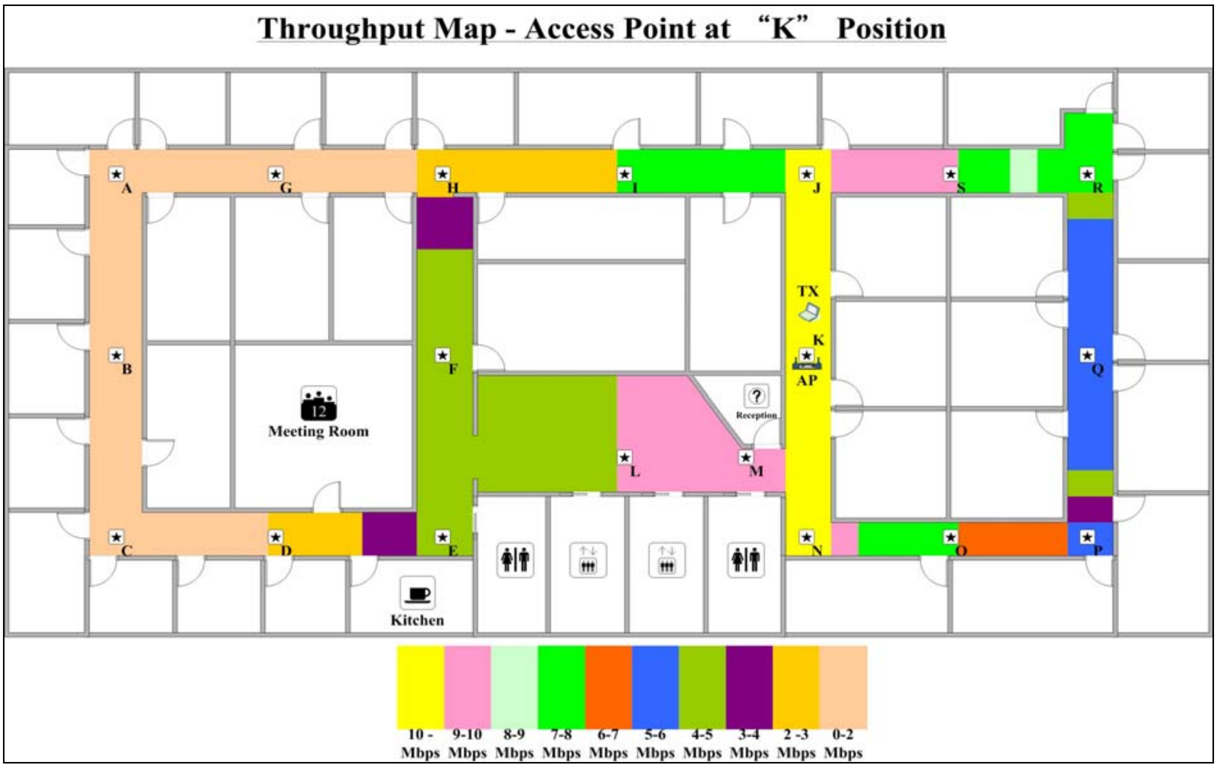


Figure B.10: Throughput map for AP at position “K”.

# Appendix C
# Phase 1 Throughput Analysis

| AP at A | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| | I | 10.325 | F | 6.965 | J | 9.337 | O | 0.393 |
| | G | 10.088 | E | 7.438 | S | 7.253 | (P-2.5m)O-P | 0.418 |
| | H | 10.088 | (H-3.5m)F-H | 8.126 | R | 5.319 | (P-3.5m)O-P | 0.422 |
| | ***Avg. TP.** | 10.167 | **Avg. TP** | 7.510 | **Avg. TP.** | 7.303 | **Avg. TP.** | 0.411 |
| | **Avg. TP.** | 8.838 Mbps | | | **Avg. TP.** | 3.857 Mbps | | |
| **Average Throughput** | | 6.384 Mbps | | | | | | |

Table C.1: Throughput analysis for AP at position “A”.

*Avg. TP.: Average Throughput (Mbps).

| AP at G | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| | H | 10.971 | C | 5.626 | I | 10.205 | (P-1.5m)O-P | 0.375 |
| | (H-1.5.5m)F-H | 10.574 | L | 6.137 | S | 9.337 | (P-1.5m)P-Q | 0.402 |
| | A | 10.448 | (C-2m)C-D | 7.566 | J | 9.238 | (P-3.5m)O-P | 0.480 |
| | **Avg. TP.** | 10.664 | **Avg. TP.** | 6.443 | **Avg. TP.** | 9.593 | **Avg. TP.** | 0.419 |
| | **Avg. TP.** | 8.554 Mbps | | | **Avg. TP.** | 5.006 Mbps | | |
| **Average Throughput** | | 6.780 Mbps | | | | | | |

Table C.2: Throughput analysis for AP at position “G”.

| AP at H | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| | F | 10.574 | C | 2.692 | I | 9.437 | (P-2.5m)O-P | 0.655 |
| | A | 10.448 | (C-2m)C-D | 3.719 | J | 8.965 | (P-1.5m)O-P | 0.714 |
| | G | 10.325 | (C-3m)C-D | 3.849 | L | 8.439 | O | 0.861 |
| | **Avg. TP.** | 10.449 | **Avg. TP.** | 3.420 | **Avg. TP.** | 8.947 | **Avg. TP.** | 0.743 |
| | **Avg. TP.** | 6.935 Mbps | | | **Avg. TP.** | 4.845 Mbps | | |
| **Average Throughput** | | 5.890 Mbps | | | | | | |

Table C.3: Throughput analysis for AP at position “H”.

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| **AP at F** | H | 9.973 | (A-2.5m)A-B | 4.302 | I | 8.521 | (R-1.5m)Q-R | 0.618 |
| | L | 9.337 | C | 4.388 | M | 8.359 | (P-1.5m)O-P | 0.741 |
| | L | 9.238 | (A-1.5m)A-B | 4.547 | J | 6.224 | (R-3.5m)Q-R | 1.178 |
| | **Avg. TP.** | 9.516 | **Avg. TP.** | 4.413 | **Avg. TP.** | 7.701 | **Avg. TP.** | 0.845 |
| | **Avg. TP.** | 6.964 Mbps | | | **Avg. TP.** | 4.273 Mbps | | |
| **Average Throughput** | | 5.619 Mbps | | | | | | |

Table C.4: Throughput analysis for AP at position "F".

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| **AP at E-3M** | H | 10.971 | (A-2.5m)A-B | 6.649 | L | 10.008 | (R-2.5m)Q-R | 1.551 |
| | (H-2m)G-H | 10.835 | A | 6.965 | I | 9.540 | (R-3.5m)Q-R | 1.607 |
| | F | 10.835 | (A-1.5m)A-B | 7.438 | M | 9.238 | R | 1.755 |
| | **Avg. TP** | 10.880 | **Avg. TP** | 7.017 | **Avg. TP** | 9.595 | **Avg. TP** | 1.638 |
| | **Avg. TP** | 8.949 Mbps | | | **Avg. TP** | 5.617 Mbps | | |
| **Average Throughput** | | 7.283 Mbps | | | | | | |

Table C.5: Throughput analysis for AP at position "E-3M".

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| **AP at I** | H | 10.574 | (C-2m)C-D | 3.389 | (J-1.5m)J-K | 10.574 | (P-2.5m)O-P | 1.836 |
| | G | 10.448 | (C-4m)B-C | 3.597 | R | 10.574 | (P-1.5m)O-P | 2.743 |
| | (H-1.5m)F-H | 10.205 | (C-2m)B-C | 4.044 | M | 10.448 | P | 3.612 |
| | **Avg. TP.** | 10.409 | **Avg. TP.** | 3.677 | **Avg. TP.** | 10.532 | **Avg. TP.** | 2.730 |
| | **Avg. TP.** | 7.043 Mbps | | | **Avg. TP.** | 6.631 Mbps | | |
| **Average Throughput** | | 6.837 Mbps | | | | | | |

Table C.6: Throughput analysis for AP at position "I".

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| **AP at L** | E | 10.835 | (A-4m)A-G | 3.157 | M | 10.835 | R | 2.831 |
| | H | 10.574 | (C-3m)B-C | 3.180 | (N-2.5m)K-N | 10.703 | (R-1.5m)S-R | 2.840 |
| | F | 10.574 | (A-3m)A-G | 3.511 | (P-2.5m)P-Q | 10.574 | (R-2.5m)Q-R | 3.157 |
| | **Avg. TP.** | 10.661 | **Avg. TP.** | 3.283 | **Avg. TP.** | 10.704 | **Avg. TP.** | 2.943 |
| | **Avg. TP.** | 6.972 Mbps | | | **Avg. TP.** | 6.823 Mbps | | |
| **Throughput Analysis** | | 6.898 Mbps | | | | | | |

Table C.7: Throughput analysis for AP at position “L”.

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| **AP at J** | I | 10.448 | (C-4m)C-D | 0.557 | S | 10.835 | O | 7.078 |
| | G | 10.205 | (C-3m)B-C | 1.458 | K | 10.448 | (P-2.5m)O-P | 7.253 |
| | H | 10.325 | C | 1.607 | R | 10.448 | L | 7.767 |
| | **Avg. TP.** | 10.326 | **Avg. TP.** | 1.207 | **Avg. TP.** | 10.577 | **Avg. TP.** | 7.366 |
| | **Avg. TP.** | 5.767 Mbps | | | **Avg. TP.** | 8.972 Mbps | | |
| **Throughput Analysis** | | 7.369 Mbps | | | | | | |

Table C.8: Throughput analysis for AP at position “J”.

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** | **RX Position** | **Highest TP.** | **RX Position** | **Lowest TP.** |
| **AP at K** | L | 9.540 | (A-2.5m)A-B | 0.643 | J | 10.574 | (P-1.5m)P-Q | 3.783 |
| | I | 7.836 | (C-3m)B-C | 0.766 | N | 10.448 | (R-1.5m)Q-R | 4.101 |
| | F | 4.822 | B | 0.823 | M | 9.861 | (P-2.5m)P-Q | 4.668 |
| | **Avg. TP.** | 7.399 | **Avg. TP.** | 0.744 | **Avg. TP.** | 10.295 | **Avg. TP.** | 4.184 |
| | **Avg. TP.** | 4.072 Mbps | | | **Avg. TP.** | 7.239 Mbps | | |
| **Throughput Analysis** | | 5.655 Mbps | | | | | | |

Table C.9: Throughput analysis for AP at position “K”.

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP** | **RX Position** | **Lowest TP** | **RX Position** | **Highest TP** | **RX Position** | **Lowest TP** |
| **AP at N-3M** | L | 9.973 | (A-3.5m)A-B | 0.752 | K | 10.835 | (R-4.5m)Q-R | 8.865 |
| | F | 8.359 | A | 0.839 | (P-1.5m)P-Q | 10.703 | (P-2.5m)P-Q | 9.540 |
| | E | 7.836 | B | 0.899 | Q | 10.703 | (R-2.5m)Q-R | 9.861 |
| | **Avg. TP** | 8.723 | **Avg. TP** | 0.830 | **Avg. TP** | 10.747 | **Avg. TP** | 9.422 |
| | **Avg. TP** | 4.776 Mbps | | | **Avg. TP** | 10.085 Mbps | | |
| **Throughput Analysis** | | 7.430 Mbps | | | | | | |

Table C.10: Throughput analysis for AP at position “N-3M”.

| | Left-Hand Area | | | | Right-Hand Area | | | |
|---|---|---|---|---|---|---|---|---|
| | **RX Position** | **Highest TP** | **RX Position** | **Lowest TP** | **RX Position** | **Highest TP** | **RX Position** | **Lowest TP** |
| **AP at R** | I | 10.205 | D | 0.596 | J | 10.703 | L | 6.501 |
| | A | 9.437 | (C-2m)C-D | 0.731 | Q | 10.703 | (N-2.5m)K-N | 7.253 |
| | H | 9.973 | (C-4m)C-D | 0.884 | S | 10.448 | M | 7.314 |
| | **Avg. TP** | 9.872 | **Avg. TP** | 0.737 | **Avg. TP** | 10.618 | **Avg. TP** | 7.023 |
| | **Avg. TP** | 5.305 Mbps | | | **Avg. TP** | 8.820 Mbps | | |
| **Throughput Analysis** | | 7.062 Mbps | | | | | | |

Table C.11: Throughput analysis for AP at position “R”.

# Appendix D
# Phase 3 Experimental Results

| TX at 2M from E-3M | | | Data File: 153.6 MB | |
|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (Seconds)** | **Throughput (Mbps)** |
| **N** | 3.00 | -42 | 220.9 | 5.562 |
| **O** | 5.41 | -51 | 231.1 | 5.317 |
| **P** | 9.49 | -58 | 249.3 | 4.928 |
| **Q** | 9.49 | -63 | 284.1 | 4.325 |
| **R** | 12.73 | -64 | 304.3 | 4.038 |
| **S** | 10.06 | -58 | 262.9 | 4.674 |
| **J** | 9.00 | -52 | 240.7 | 5.105 |
| **K** | 3.00 | -48 | 226.2 | 5.432 |
| **I** | 10.82 | -72 | 379.1 | 3.241 |
| | | | **Average Throughput** | 4.736 |

Table D.1: Numerical results for WDS with AP mode, TX at BSS1.

| TX at 2M from N-3M | | | Data File: 153.6 MB | |
|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (Seconds)** | **Throughput (Mbps)** |
| **E** | 3.00 | -45 | 230.4 | 5.332 |
| **D** | 5.83 | -59 | 262.4 | 4.683 |
| **C** | 11.40 | -63 | 291.3 | 4.218 |
| **B** | 11.40 | -68 | 284.1 | 4.325 |
| **A** | 14.21 | -72 | 427.7 | 2.873 |
| **G** | 10.30 | -64 | 346.9 | 3.542 |
| **H** | 9.00 | -58 | 251.9 | 4.877 |
| **F** | 3.00 | -52 | 236.7 | 5.192 |
| **I** | 10.82 | -67 | 290.0 | 4.237 |
| | | | **Average Throughput** | 4.364 |

Table D.2: Numerical results for WDS with AP mode, TX at BSS2.

| TX at 2M from E-3M | | | Data File: 153.6 MB | |
|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (Seconds)** | **Throughput (Mbps)** |
| **N** | 3.00 | -44 | 80.8 | 15.213 |
| **O** | 5.41 | -49 | 82.8 | 14.832 |
| **P** | 9.49 | -56 | 84.2 | 14.589 |
| **Q** | 9.49 | -65 | 87.2 | 14.087 |
| **R** | 12.73 | -64 | 89.3 | 13.764 |
| **S** | 10.06 | -57 | 87.6 | 14.034 |
| **J** | 9.00 | -54 | 82.7 | 14.866 |
| **K** | 3.00 | -48 | 82.0 | 14.991 |
| **I** | 10.82 | -70 | 96.4 | 12.749 |
| | | | **Average Throughput** | 14.347 |

Table D.3: Numerical results for AP mode with Ethernet, TX at BSS1.

| TX at 2M from N-3M " | | | Data File: 153.6 MB | |
|---|---|---|---|---|
| **RX Position** | **Distance from AP (Meter)** | **Signal Strength (dBm)** | **Time (Seconds)** | **Throughput (Mbps)** |
| **E** | 3.00 | -46 | 86.3 | 14.231 |
| **D** | 5.83 | -58 | 88.5 | 13.879 |
| **C** | 11.40 | -63 | 93.6 | 13.127 |
| **B** | 11.40 | -70 | 89.4 | 13.749 |
| **A** | 14.21 | -75 | 102.7 | 11.961 |
| **G** | 10.30 | -65 | 91.5 | 13.436 |
| **H** | 9.00 | -57 | 87.8 | 13.992 |
| **F** | 3.00 | -53 | 87.1 | 14.112 |
| **I** | 10.82 | -69 | 95.8 | 12.823 |
| | | | **Average Throughput** | 13.749 |

Table D.4: Numerical results for AP mode with Ethernet, TX at BSS2.

# Appendix E
# D-Link Product Specifications

## IEEE 802.11 b/g Access Point

DWL-2100AP Data Sheet available at

ftp://ftp10.dlink.com/pdfs/products/DWL-2100AP/DWL-2100AP_ds.pdf

DWL-2100AP FAB Sheet available at

ftp://ftp10.dlink.com/pdfs/products/DWL-2100AP/DWL-2100AP_fab.pdf

## IEEE 802.11 b/g Wireless Adapter

DWL-G132 Data Sheet available at

ftp://ftp10.dlink.com/pdfs/products/DWL-G132/DWL-G132_ds.pdf

DWL-G132 FAB Sheet available at

ftp://ftp10.dlink.com/pdfs/products/DWL-G132/DWL-G132_fab.pdf

## 2.4 GHz Omni-Directional 7dBi Indoor Antenna

ANT24-0700 Data Sheet available at

ftp://ftp10.dlink.com/pdfs/products/ANT24-0700/ANT24-0700_ds.pdf

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- **Up to 108Mbps[1] with D-Link 108G Products**
- Improved Wireless Security with WPA and 802.1X Authentication
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# 108Mbps[1] Access Point

D-Link, the industry pioneer in wireless networking, introduces a performance breakthrough in wireless connectivity – **D-Link *Air*Plus *Xtreme G*™** series of high-speed devices now capable of delivering transfer rates up to 15x faster than the standard 802.11b with the new D-Link 108G. With the new *Air*Plus *Xtreme G* DWL-2100AP Wireless Access Point, D-Link sets a new standard for wireless access points.

With the D-Link 108G enhancement, the DWL-2100AP can achieve wireless speeds up to 15x in a pure D-Link 108G environment through the use of new wireless technologies such as Packet Bursting, Fast Frame, Compression & Encryption, and Turbo mode.These technologies enable a throughput high enough to handle video/audio streaming and future bandwidth-intense applications. The DWL-2100AP also supports SNMP v.3 for better network management with the provided Wireless AP Manager software that manages network configuration and firmware upgrades. For Enterprise networks, the DWL-2100AP supports network administration and real-time network traffic monitoring via D-Link's D-View Network Management software.

The DWL-2100AP features WDS (Wireless Distribution System) that can be configured to perform in any one of five modes: a Wireless Access Point, a Point-to-Point (PtP) bridge with another DWL-2100AP, a Point-to-Multipoint (PtMP) bridge, a Repeater for range extension, or as a Wireless Client. The WDS feature makes the DWL-2100AP an ideal solution for quickly creating and extending a wireless local area network (WLAN) in offices or other workplaces, or even at hotspots.

Wireless security is addressed as the DWL-2100AP uses WPA (Wi-Fi Protected Access) and 802.1X authentication to provide a higher level of security for data communication amongst wireless clients. The DWL-2100AP is also fully compatible with the IEEE 802.11b and 802.11g standards. With great manageability, versatile operation modes, solid security enhancement, the cost-effective D-Link *Air*Plus *Xtreme G* DWL-2100AP Wireless Access Point provides the ultra-fast wireless signal rates and everything else a network professional dreams of.

# AirPlus Xtreme G®

DWL-2100AP

## 802.11g/2.4GHz Wireless

# 108Mbps[1] Access Point

## SPECIFICATIONS

**Standards**
- IEEE 802.11g
- IEEE 802.11b
- IEEE 802.11
- IEEE 802.3
- IEEE 802.3u

**Device Management**
- Web-Based – Internet Explorer v6 or later; Netscape Navigator v6 or later; or other Java- enabled browsers.
- SNMP v.3

**Wireless Distribution System**
- AP Client
- PtP Bridge
- PtMP Bridge
- Repeater

**Security**
- 64-, 128 152-bit WEP
- 802.1X (EAP-MD5, EAP-TLS, EAP-TTLS and EAP-PEAP)
- WPA —Wi-Fi Protected Access
- MAC Address Access Control (WPA-TKIP and WPA-AES)

**Media Access Control**
CSMA/CA with ACK

**Wireless Frequency Range**
2.4GHz to 2.4835GHz

**Wireless Operating Range**[2]
Indoors: Up to 328 ft (100 meters)
Outdoors: Up to 1312 ft (400 meters)

**Modulation Technology**
- Orthogonal Frequency Division Multiplexing (OFDM)
- Complementary Code Keying (CCK)
- DQPSK
- DBPSK

**Wireless Transmit Power**
15dBm (32mW) ± 2dB
(Control TX power level from full, 50%, 25%, 125% and min.)

**Receiver Sensitivity**
- 54Mbps OFDM, 10% PER,-66dBm)
- 48Mbps OFDM, 10% PER,-71dBm)
- 36Mbps OFDM, 10% PER,-76dBm)
- 24Mbps OFDM, 10% PER,-80dBm)
- 18Mbps OFDM, 10% PER,-83dBm)
- 12Mbps OFDM, 10% PER,-85dBm)
- 11Mbps CCK, 8% PER,-83dBm)
- 9Mbps OFDM, 10% PER,-86dBm)
- 6Mbps OFDM, 10% PER,-87dBm)
- 2Mbps QPSK, 8% PER,-89dBm)

**External Antenna Type**
1.0dB Dipole with reverse SMA connector

**LEDs**
- Power
- LAN (10/100)
- WLAN (Wireless Connection)

**Temperature**
- Operating: 32°F to 140°F (0°C to 40°C)
- Storing: 4°F to 149°F (-20°C to 65°C)

**Humidity**
95% maximum (non-condensing)

**Power Input**
Ext. Power Supply DC 5V, 2.0A

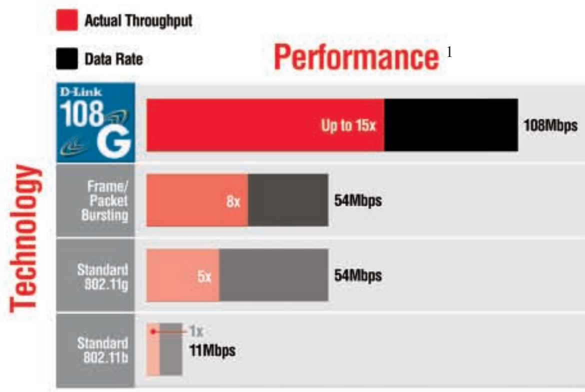
**Safety & Emissions**
- FCC • UL • VCCI • CSA • EN

**Dimensions**
- L = 5.6 inches (142mm)
- W = 4.3 inches (109mm)
- H = 1.2 inches (31mm)

**Weight**
0.44 lbs (200g)

**Warranty**
3 Year

[1] Maximum wireless signal rate derived from IEEE Standard 802.11g specifications. Actual data throughput will vary. Network conditions and environmental factors, including volume of network traffic, building materials and construction, and network overhead lower actual data throughput rate.
[2] Environmental conditions may adversely affect wireless signal range.




D-Link performance results are based on testing with other D-Link 108G enabled devices utilizing Packet Burting, FastFrames, Turbo Mode and Compression techniques. Data already compressed may not benefit from the D-Link 108G compression technique.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AirPlus XtremeG

*108Mbps[1] Wireless Networking*

**DWL-2100AP**

***802.11g/2.4GHz Wireless Access Point***

# Features and Benefits

**Faster Wireless Networking**

Able to achieve a maximum wireless signal rate of up to 108Mbps[1], increased speeds means increased productivity. With the DWL-2100AP in your home or business, colleagues, friends, or family can communicate with one another in real-time to download large files or to smoothly stream MPEG videos. The DWL-2100AP Wireless Access Point gives you the freedom of wireless networking at D-Link 108G speeds that save you time, money, and make your wireless networking experience more enjoyable.

**SNMP Management**

The DWL-2100AP is not only fast but it also supports SNMP v.3 for better network management. A Wireless AP Manager software is available with the DWL-2100AP for network configuration and firmware upgrades via a web-based configuration utility. For Enterprise networks, the DWL-2100AP supports network administration and real-time network traffic monitoring via D-Link's D-View Network Management software.

**Better Security with 802.1X and WPA**

With the DWL-2100AP, wireless clients can securely connect to the network using WPA (Wi-Fi Protected Access) and 802.1X authentication providing a much higher level of security for your data communication. AES (Advanced Encryption Standard) is also supported by the DWL-2100AP to maximize the network security with data encryption.

**Five Different Operating Modes**

The DWL-2100AP can operate in one of five different operational modes featuring WDS (Wireless Distribution System) to meet your wireless networking requirements:

**Access Point** — Create a wireless local area network.

**Point-to-Point Bridging** — Wirelessly connect two networks. This mode provides a cost-effective solution when traditional wired solutions are too costly or prohibitive.

**Point-to-Point Multipoint Bridging** — Wirelessly connect multi-networks. This mode acts as a hub to connect multiple wireless networks.

**Wireless Client** — Wirelessly connect Ethernet devices. Provides immediate connection for Ethernet devices without the need for any drivers.

**Repeater** — Repeats radio frequency to extend the 2.4GHz range for your wireless LAN.

**Other D-Link Products that work with DWL-2100AP:**

**DWL-G650**
**High-Speed 802.11g**
**Wireless Cardbus Adapter**

**DWL-G520**
**High-Speed 802.11g**
**Wireless PCI Adapter**

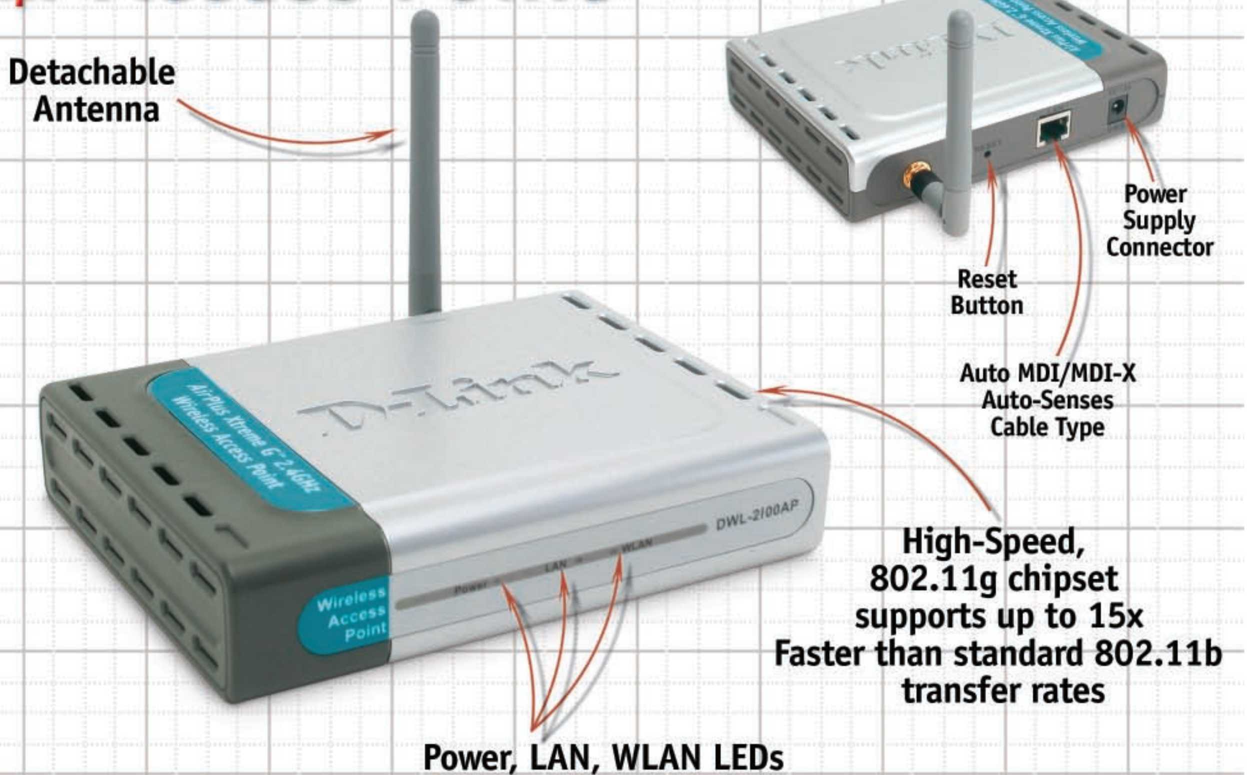
**DI-624**
**High-Speed 802.11g**
**Wireless Router**

AirPlus Xtreme G®

DWL-2100AP

# 802.11g/2.4GHz Wireless

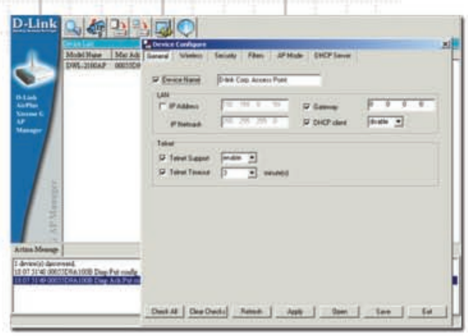
# 108Mbps[1] Access Point




## Five Operational Modes

| Operation Mode (Only supports 1 mode at a time) | Function |
|---|---|
| Access Point (AP) | Create a Wireless LAN |
| AP - to - AP Bridging | Wirelessly Connect 2 Networks |
| Point - to - Multipoint Bridging | Wirelessly Connect Multi Networks |
| Wireless Client | Wirelessly Connect Ethernet Devices |
| Wireless Repeater (WDS)* | Wireless Repeats 11g AP Gateways (Atheros Based) |

*WDS Includes Bridge Repeating

[1] Maximum wireless signal rate derived from IEEE Standard 802.11g specifications. Actual data throughput will vary. Network conditions and environmental factors, including volume of network traffic, building materials and construction, and network overhead lower actual data throughput rate.

**Product Information**
Part No: DWL-2100AP
Description: 802.11g/2.4GHz Wireless Access Point
UPC: 790069-263958
D-Link Systems, Inc.
TEL: (800) 326-1688
www.dlink.com

The Window-based managementrt software of the DWL-2100AP allows you to reconfigure the AP in any one of its five operating modes or to apply other management settings.

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# 802.11g Wireless Connectivity Via USB

- Adds 802.11g Wireless Connectivity to a Desktop or Notebook PC
- USB Connectivity for Convenient Setup
- Enhanced Wireless Performance Powered by D-Link 108G Technology
- Connects to 802.11b/g Wireless Networks
- Protects Your Network with WPA and 802.1x Security

DWL-G132

G 108

AirPlus Xtreme G®

## Wireless 108G

# USB Adapter

D-Link, the industry pioneer in wireless networking, introduces the DWL-G132 Wireless USB Adapter, part of the *Air*Plus *Xtreme G*® family of 802.11g wireless networking devices. Powered by D-Link 108G Technology, this 802.11g compatible device is capable of delivering maximum wireless signal rates of up to 108Mbps[1] when connected to other D-Link *Air*Plus *Xtreme G* products.

The DWL-G132 is a convenient wireless connectivity solution for desktop or notebook PCs. Instead of stringing Ethernet cables to your PC or dismantling your desktop computer case, the DWL-G132 enables 802.11g wireless connectivity by simply utilizing your desktop or notebook PC's USB port.

Featuring the latest in wireless technology, the DWL-G132 delivers unparalleled performance and industry-wide compatibility. With a maximum wireless signal rate of up to 108Mbps[1], quickly transfer large files or view streaming video with the DWL-G132.

The DWL-G132 includes an intuitive configuration utility that allows you to discover and connect to other wireless networks in nearby areas. In addition, the utility can also create detailed connectivity profiles of networks you frequently access. You can also enable support for WPA and 802.1x for enhanced data encryption and user authentication.

Like all other D-Link wireless adapters, the DWL-G132 can be used in peer-to-peer mode (ad-hoc) to connect directly to other 802.11b/g wirelessly enabled computers or in client mode (infrastructure) to communicate with other users through an access point or router.

Compact in size, robust in speed the DWL-G132 Wireless USB Adapter is great for travel and a convenient solution for providing high performance wireless connectivity to your desktop or notebook PC. Enjoy the many benefits of wireless connectivity today!

# AirPlus Xtreme G®

## Wireless 108G

# USB Adapter

**DWL-G132**

## SPECIFICATIONS

**Standards**
- 802.11b
- 802.11g
- USB 2.0
- USB 1.1

**Device Management**
- D-Link Wireless Utility

**Data Rate**[1]
- 802.11b - 11, 5.5, 2 and 1Mbps
- 802.11g - 108, 54, 48, 36, 24, 18, 12, 9 and 6Mbps

**Security**
- WEP 64/128bit
- WPA-Personal
- WPA-Enterprise (includes 802.1x)

**Wireless Frequency Range**
- 2.4GHz – 2.5GHz (2400MHz – 2497MHz)

**Wireless Operating Range**[2]
- Indoors: Up to 328 feet (100 meters)
- Outdoors: Up to 1,312 feet (400 meters)

**Modulation Technology**
- 11g – OFDM, 64QAM, 16QAM, QPSK BPSK
- 11b – CCK, DSSS, DBPSK, DQPSK

**Receiver Sensitivity**
- 802.11b : -82dBm for 11Mbps @ 8% PER
- 802.11b : -87dBm for 2Mbps @ 8% PER
- 802.11g: -88dBm at 6Mbps @ 10% PER
- 802.11g: -86dBm at 9Mbps @ 10% PER
- 802.11g: -84dBm at 12Mbps @ 10% PER
- 802.11g: -82dBm at 18Mbps @ 10% PER
- 802.11g: -78dBm at 24Mbps @ 10% PER
- 802.11g: -74dBm at 36Mbps @ 10% PER
- 802.11g: -69dBm at 48Mbps @ 10% PER
- 802.11g: -66dBm at 54Mbps @ 10% PER

**Wireless Transmit Power**
- 11b – 16dBm @ 11, 5.5, 2 and 1Mbps
- 11g – +15dBm @ 54 and48Mbps
- 11g – +16dBm @ 36Mbps
- 11g – +17dBm @ 24, 18, 12, 9 and 6Mbps

**External Antenna Type**
- Integrated Antenna

**LEDs**
- Activity
- Link

**Power Consumption**
- 472 mA in continuous transmit mode
- 290 mA in continuous receive mode

**Temperature**
- Operating in 0C to +40C
- Non-Operating -20C to +75C

**Humidity**
- Operating in 20% - 80% non-condensing
- Non-operating in 5% to 95% non-condensing

**Certifications**
- FCC
- UL

**Dimensions**
- L – 81mm
- W – 25mm
- H – 1.3mm

**Weight**
- .006lbs

**Warranty**
- 1 Year

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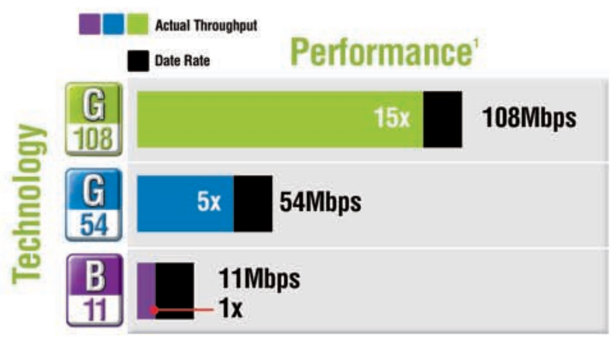
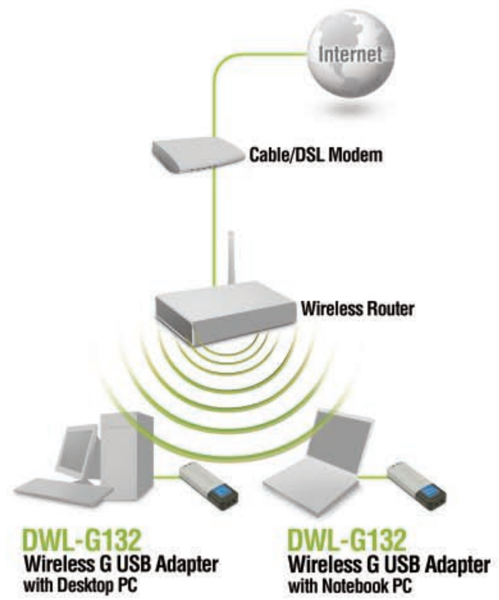
[2] Environmental conditions may adversely affect wireless signal range.




D-Link *Air*Plus *Xtreme G* products are capable of delivering wireless signal rates of up to 15x faster than 802.11b.



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*802.11g Wireless Connectivity Via USB*

# DWL-G132 *Wireless 108G USB Adapter*

# Features and Benefits

### Add 802.11g Wireless Connectivity to Your PC at up to 108Mbps[1]

Experience the freedom of wireless connectivity. With the DWL-G132 connected to your desktop or notebook PC, you can enjoy the benefits of 802.11g wireless networking. The DWL-G132 offers a maximum wireless signal rate of up to 108Mbps[1] giving you plenty of bandwidth needed to videoconference with colleagues in real-time, stream video, or transfer large files quickly. Enjoy the mobility of wireless networking.

### USB Connectivity for Convenient Setup

Its attractive and compact design allows you to take the DWL-G132 wherever you go. It fits easily into notebook carrying cases, briefcases, backpacks, or even your pocket. When you're ready to connect, simply plug in the DWL-G132 to an available USB port on your notebook or desktop PC.

### Connect to 802.11b/g Wireless Networks and Hotspots

The DWL-G132 is also backward compatible with the 802.11b standard, so it can connect to the increasing number of wireless hotspots available. With the DWL-G132, enjoy wireless connectivity wherever it may be available–in your office, on your deck or patio, by the pool, at the local coffee shop, or in an airport terminal while you are waiting to board your next flight.

### Protect Your Network with WPA and 802.1x User Authentication

With the DWL-G132, you can securely connect to a wireless network using WPA (Wi-Fi Protected Access), which provides you with advanced encryption for your wireless connection. 802.1x user authentication provides an extra layer of protection for your sensitive information.

**Other D-Link products that work with the DWL-G132:**

**DI-624**
**Wireless 108G Router**

**DWL-G650**
**Wireless 108G Cardbus Adapter**

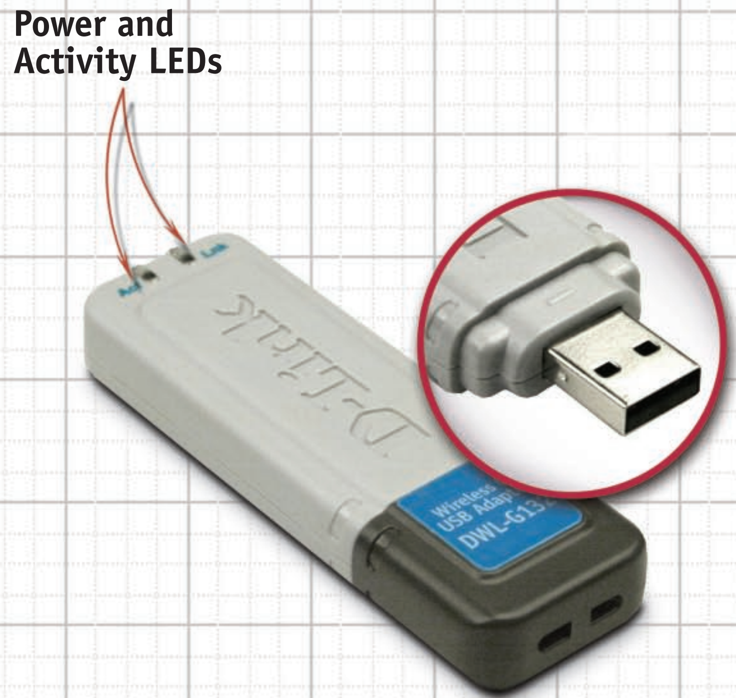
**DWL-2100AP**
**Wireless 108G Access Point**

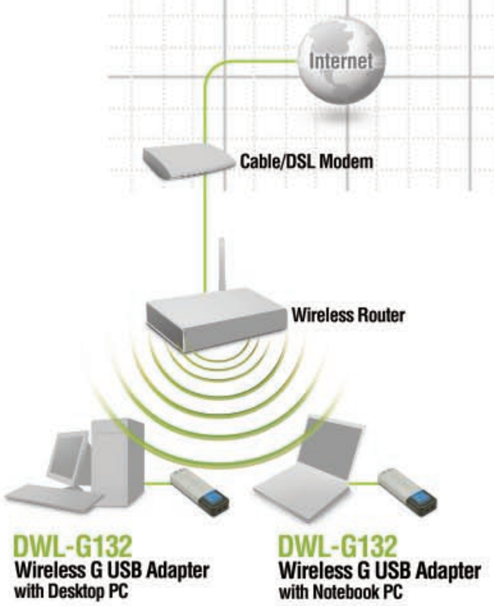
# AirPlus Xtreme G®

## Wireless 108G

# USB Adapter

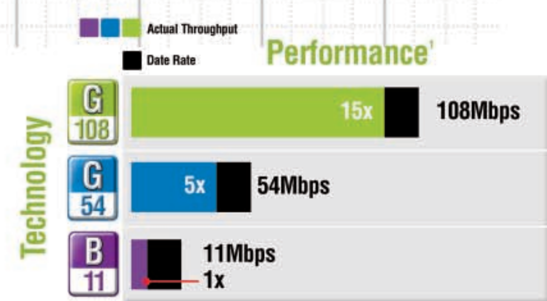
**DWL-G132**




Add 802.11g Wireless connectivity to any USB-enabled device and avoid the hassle of network cables.


**Product Information**
Part No: DWL-G132
Description: Wireless 108G USB Adapter
UPC: 790069-262043
D-Link Systems, Inc.
TEL: (800) 326-1688
www.dlink.com




D-Link *Air*Plus *Xtreme G* products are capable of delivering wireless signal rates of up to 15x faster than 802.11b.

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# Extend Your Wireless Signal in All Directions

ANT24-0700

- 7dBi Omni-Directional Antenna for Extended Wireless Signal Range
- Powerful Signal Reception in All Directions
- Works with Virtually Any 802.11b/g Compliant Devices with a SMA or TNC Connector
- Magnetic Base[1] with Extension Cable and Mounting Kit for Flexible Placement

# 2.4GHz Omni-Directional 7dBi Indoor Antenna

D-Link, an industry leader in networking, introduces the ANT24-0700 Omni-Directional 7dBi Indoor Antenna designed to provide extended coverage for an existing 802.11b/g wireless network.

The omni-directional design of the ANT24-0700 offers dramatically increased wireless signal coverage in all directions. With 360° of better signal reception, this high-gain antenna will also improve data throughput at further distances.

The D-Link ANT24-0700 connects to a variety of wireless routers and access points on the market today. Whether the wireless router or access point has a SMA or TNC connector, the ANT24-0700 comes with a RP-SMA to RP-TNC conversion adapter to accommodate either connector type.

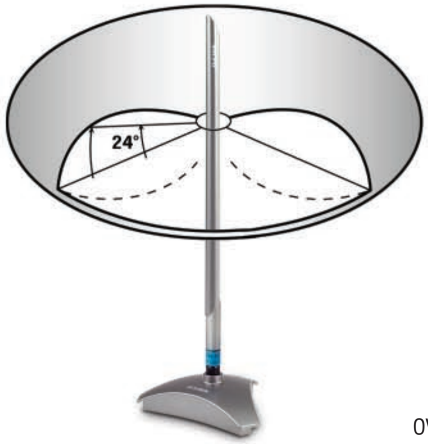
For maximum flexibility in placement, the ANT24-0700 comes with a magnetic base unit[1] with 1.5m extension cable, and a mounting kit. The magnetic base unit has a incredible strong hold onto any metal surface.

Avoid the cost and complexity of adding additional access points or repeaters when you can easily use the ANT24-0700. Enjoy the benefits of wireless connectivity at greater distances throughout your home or small office.

[1] Warning: The base unit is magnetic. Keep magnetic base at least 6 inches away from electronic devices; computers, TV's, video equipment, and tapes. Exposure to magnetic base may cause device or data on disks to become corrupted.

# 2.4GHz Omni-Directional
# 7dBi Indoor Antenna

ANT24-0700




## SPECIFICATIONS

**Frequency Range**
- 2.4GHz – 2.5GHz

**Gain**
- 7dBi

**Voltage Standing Wave Ratio (VSWR)**
- 1.92 : 1 Max

**Polarization**
- Linear, Vertical

**Half Power Beam Width (HPBW)**
- Horizontal - 360 degrees
- Vertical - 24 degrees

**Impedance**
- 50 Ω (Ohms) Nominal

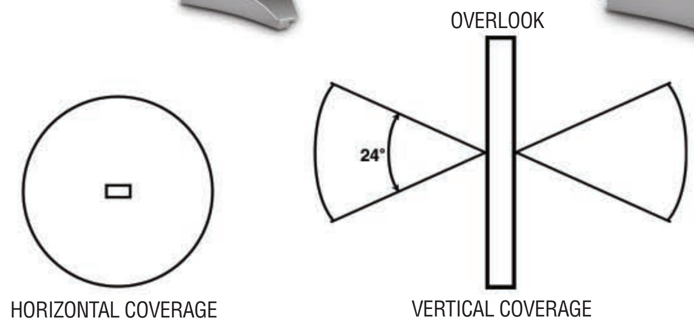
**Connector**
- Reverse SMA
- RP-SMA to TNC Adapter

**Cable**
- 1.5m RG-178 50 Ω (Ohms)

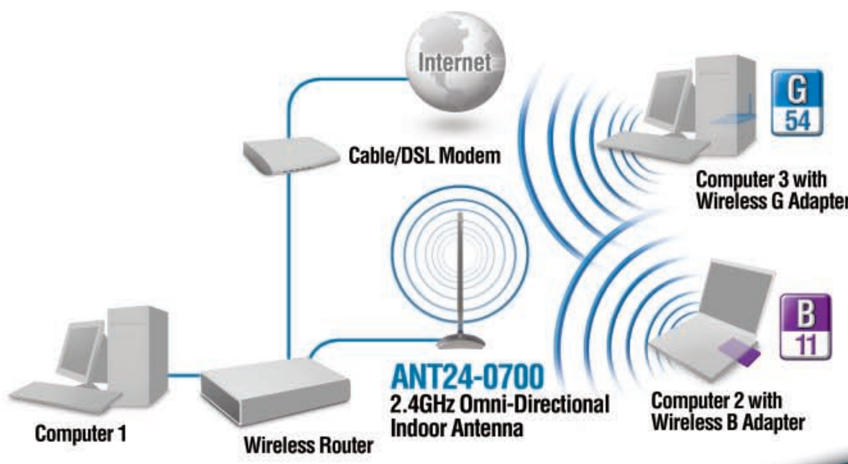
**Operating Temperature**
- -4° F to 149° F (-20° C to +65° C)

**Storage Temperature**
- -22° F to 167° F (-30° C to +75° C)

**Warranty**
- 1-Year




Add the ANT24-0700 to your 802.11b/g wireless router or access point for additional wireless coverage in all directions.





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