PROPAGATION CHARACTERISTIC MEASUREMENT AND FREQUENCY REUSE PLANNING IN A CAMPUS ENVIRONMENT

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Abstract

The indoor propagation loss of radio wave had been measured in a ten-story university building by sending an low level unmodulated carrier from a transmitter and received by a spectrum analyzer. The building possessed concrete floors and walls with plasterboard internal partition and pipes hidden above the false ceiling. Measurement was performed in frequencies 250MHz, 400MHz, 800MHz, 1.1GHz and 1.5GHz. The results measured with different frequencies were compared so as to determine the most suitable frequency band and base station locations for an indoor digital radio communication system in typical office environment. The same method was also used to measure the propagation loss on three adjacent floors in an university student hostel, where the internal shape and partition materials are completely different from the university building. The results of this measurement were used to examine the accuracy of the model. With the measurements, the attenuation of different kinds of internal partition materials in different frequencies was determined. The propagation loss to the adjacent floors and neighboring building was also measured for frequency reuse planning. The effect on building penetration, the results different from theory and previous measurements were also studied. The multipath characteristic was also measured in the university building with a close transmitter

and receiver separation.

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Chapter 1

Introduction

The information accessing in today's university community is generally performed by wired connection, such as telephone lines for facsimiles and person-to-person voice conversations, and cables for computers, workstations, and printers. These interconnections are essential for transferring information and sharing expensive equipment. However, the hard wiring, a conventional procedure for joining two sets of machinery, is found to be expensive and time consuming on installation and maintenance in office buildings.

Before the advanced radio technology became available, the wired systems are accepted inevitably due to the lack of possible alternatives. With up-to-date radio technologies, the inconvenience caused by installation, relocation, and maintenance of the hard wiring can be completely avoided and a campus-sized local area network (LAN) that provides high performance and true mobility is possible.

When the number of wireless terminals started to grow in indoor environment, there were two approaches to implement: one using infrared radiation and the other using spread-spectrum microwave technology [1]. Since the depth of penetration of an electromagnetic signal is inversely proportional to the square root of its frequency, therefore optical signals, ranging approximately 10^5GHz, cannot penetrate wall and furniture. It is also very easy to be interfered by strong ambient light. Those factors limited the use of infrared in terminals with true mobility. Nowadays, infrared is the most popular medium on remote control of audio-visual appliances. Spread-spectrum technique is widely used on wireless LAN.

With the subscriber radio terminals operated under indoor environment, either leaky feeder or antenna can be used on the base stations to transmit and receive radio signal to and from the subscriber terminals. Palmer and Motley [2] reported that by using leaky feeder to direct radio signals, the signal level would be more even than that of antenna especially at extreme range, at the same time the protection against interference from other cochannel users could be increased. The coverage would be highly predictable and can be calculated by using only a few propagation parameters. In a cellular environment, the cell size can be precisely defined and the interference to the cochannel cells will be reduced to minimum. However, leaky feeder is very expensive in comparison to indoor antenna. Even the subscribers can have true mobility, the installation and maintenance of the leaky feeder has the same difficulty as the wired system. Therefore, antennas are used on most of the base stations in the practical indoor radio communication systems. With the exceptional cases of confined areas such as mines, basements and tunnels, satisfactory coverage is very hard to be realized by using antenna on the base station unless quasi-synchronous technique [3] is applied, then leaky feeder will be more favorable to the users.

The need to provide a cost-effective wireless information service at an environment of university campus originated our study on radio propagation measurement. Department of Information Engineering, the Chinese University of Hong Kong is now implementing a mobile communication system prototype known as VIP Net, a Voice Interactive Paging System. It is a two-way, digital communication system for textual and vocal message. The immediate goal is to build a system with three cell sites in the university. The base stations of all cell sites are interconnected by an FDDI network and routing will be performed via a central switching and processing element. The VIP Net users can send message to each other by means of voice and text through the base stations. With accurate propagation model and measurement, both performance and cost can be optimized. There are three parameters affecting base site location, type of equipment and frequency planning:

1. Propagation loss
2. Building penetration
3. Multipath characteristic

Propagation loss in a commercial building will not be uniform in comparison to the outdoor environment. It will be affected by the size and internal shape of building. Furniture, partitions, cabinets, and the walls between offices will create additional loss. On the other hand, propagation along a corridor will have less attenuation than free space.

In urban area, the building density is very high. The radio energy transmitted from one equipment will not only penetrate to the adjacent floors, it will also penetrate the neighboring buildings and even the buildings on the opposite side of the street. Moreover, if there are two buildings much taller than the buildings between them, the offices on the higher floors of these buildings will have clear line of sight between each other. Therefore, frequency planning will be essential on preventing interference if several offices nearby are operating radio equipment, even though the tinted glass or metallic shade on the windows may creat attenuation and the transmitter output power will not usually be higher than 100mW in a picocell environment.

When the transmitter and receiver are located in the same building with the distance to the walls only in tens of meters, the signals received from the direct path and the reflected path will only different in typically less than 100ns if the transmitter output power is low. Moreover, the strength of those signals will not have a large difference and will caused intersymbol distortion. The bit rate must be limited to allow reliable transmission.

For an indoor radio communication system, the choice on operating frequency will affect the system performance and system design. The indoor radio systems available in the market nowadays are working in different frequency bands. For example, cordless telephone is working on 1.7MHz and 47MHz, CT2 on 865MHz, PCN on 1.8GHz and wireless LAN on 2.4GHz [4]. 1.7MHz is definitely too low, equipment will need a large size antenna to transmit and receive efficiently. Motley [5] found that 40MHz had higher attenuation over the higher frequencies under indoor environment. On the other hands, frequencies in tens of gigahertz has limitation on communication applications. Alexander and Pugliese [6] had measured the propagation characteristics of 60GHz radio wave, they found that it was very hard to penetrate metal. It makes 60GHz not suitable to be used with coverage area larger than a room. Frequency selective absorption of atmosphere results at high frequencies. The first peak of absorption due to water vapor occurs around 24GHz, and that of oxygen occurs at about 60GHz. With the above mentioned considerations and the availability of test instruments, the frequencies chosen for our measurement were from 250MHz to 1.5GHz.

The antennas used in most of the existing mobile communication systems are vertical polarized, but because of handset orientation, the mobile antenna will not always be copolarized with the base antenna. If the transmitting and receiving antennas are not in line of sight, the receiving antenna of copolarized and crosspolarized will exhibit equal average signal levels and deep fading with low correlation [7]. In case of line of sight, the copolarized antenna will have higher received signal level. In our measurement, the relationship between the loss of line of sight path and non line of sight paths had to be examined. Therefore, only vertical polarized antennas were used for both transmitter and receiver.

The indoor propagation loss and multipath characteristic had been measured in Ho Sin Hang Engineering Building and Postgraduate Hostel of The Chinese University of Hong Kong. For propagation loss, 250MHz, 400MHz, 800MHz, 1.1GHz and 1.5GHz were measured, 800MHz, 1.1GHz and 1.5GHz were measured on multipath characteristics.

The building penetration measurement was done in three parts:

1. Penetration between floors

2. Penetration between neighboring buildings

3. Penetration between buildings further apart with clear line of sight

For part one, the measurement was performed between floors and the floor attenuation factors were measured. For part two, the atrium in Ho Sin Hang

Engineering Building was used to simulate a narrow street between buildings and for part three, measurement was performed between Ho Sin Hang Engineering Building and Lady Shaw Building.

In what follows, some previous works on propagation loss and multipath characteristics measurement are reviewed in Chapter 2. The propagation model will be described in Chapter 3. In Chapter 4, the measurement sites and setup are presented. The measurement results in terms of propagation and penetration loss as well as multipath characteristics are presented in Chapter 5. Frequency reuse planning and limitations of the measurements are presented in Chapter 6 and the conclusions are drawn in Chapter 7. Finally, the method of calculating propagation loss slope from the recorded signal level in the measurements is discussed in Appendix A.

Chapter 2

Background of Measurement in Indoor Environment

Since Marconi worked on practical radio communication system in 1895 [3], except for broadcasting, radio was mainly used on mobile communications. In the beginning, radio was used on transmitting telegraph signal. When technology getting mature, voice, and later high bit rate digital signal, could be transmitted by means of radio wave. No matter what frequency band is used, regardless the subscriber terminals are fixed or moving, propagation loss is a major parameter to be considered in designing a radio communication system. It affects the choice of antenna, transmitter output power and the coverage area. If propagation loss is underestimated, there will be black areas in the expected coverage. If it is overestimated, black areas will be minimized but the excessive output power will interfere the systems nearby. In case of a cellular system, it will resulted as reducing the system capacity [8]. To determine the propagation loss in an area is a tedious work. Therefore, different models were introduced to let the engineers have a rough idea how the channel will behave before they perform the field measurement. Hence field measurement can be further simplified.

Multipath characteristics is also an important factor in system design. When radio wave propagates from transmitter to receiver, energy will arrive simultaneously in different paths [3]. They combine vectorially at the receiver antenna to give a resultant signal which can be large or small depending on the distribution of phases amongst the component waves. The signal fluctuations are known as fading. The effect of fading can easily be observed from short wave broadcasting. It is caused by signal propagating via ground wave (over the earth surface) and sky wave (reflecting between earth surface and ionosphere). In broadcasting, it only affects the received audio signal quality but in digital communication, it will end up with intersymbol interference and high bit error rate.

In this chapter, basic concept on propagation measurement, previous works on path loss and multipath measurement are reviewed.

2.1 Propagation loss

In this section, some basic concepts refer to Yacoub [9], and the previous works in indoor environment propagation prediction and measurement are reviewed.

2.1.1 Basic concepts

When power W is radiated out from an isotropic source, if the medium is lossless, the received power density P at a distance d can be shown from the free space transmission formula [10]

$$P = \frac{W}{4\pi d^2} \tag{2.1}$$

If the source is not isotropic, the received power density can be shown as the equation below

$$P = \frac{G_t W_t}{4\pi d^2} \tag{2.2}$$

where W_t is the input power of the transmitting antenna and G_t is the transmitting antenna gain. Then $G_t W_t$ is the effective radiated power from the transmitting antenna.

Total power received by the load at distance d is

$$W_r = A_r P \tag{2.3}$$

where A_r is the antenna aperture.

By substituting equation(2.2) into equation(2.3)

$$W_r = \frac{A_r G_t W_t}{4\pi d^2} \tag{2.4}$$

When the transmitting and receiving antennas both have unity efficiency, the path loss, i.e., ratio between received power W_r and transmitted power W_t, can be shown as

$$\frac{W_r}{W_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{2.5}$$

where G_r is receiving antenna gain and λ is wavelength of the signal transmitted. Equation(2.5) is known as the Friis free space transmission formula. In decibel, the path loss L is given as

$$L = -10 \log W_r + 10 \log W_t \tag{2.6}$$

Accordingly, the path loss (in decibel) is

$$L = -10 \log G_t - 10 \log G_r - 20 \log \lambda + 20 \log d + 21.98 \tag{2.7}$$

If the gain of antennas and wavelength remain unchanged, path loss can simply be represented as

$$L \propto d^{-2} \tag{2.8}$$

In most of the applications on land, both transmitting and receiving antennas are located nearby the ground. In case the radio wave is propagated in a flat-terrain with frequency higher than 100MHz and incidence angle less than 10°, the path loss can be represented by the inverse fourth-power loss formula [9]

$$\frac{W_r}{W_t} = G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2 \tag{2.9}$$

where h_t and h_r are the height of transmitting and receiving antennas respectively. The corresponding path loss in decibels is

$$L = -10 \log G_t - 10 \log G_r - 20 \log h_t h_r + 40 \log d \tag{2.10}$$

or

$$L \propto d^{-4} \tag{2.11}$$

if G_t, G_r, h_t and h_r are kept constant.

This formula is a simplified model. In real life, it is very rare to have a real flat-terrain, then diffraction loss caused by obstructions has to be considered. A mathematical approach to deal with this situation is rather complicated and no simple solution is available. There were approximate methods proposed for outdoor propagation loss prediction to allow engineers having a rough idea on path loss before performing field measurement. However, according to different assumptions the methods made, we have to bear in mind that different places should apply different methods to acheive a more precise prediction.

In outdoor environment, the obstructions on the propagation path can be modeled as objects having knife-edge diffraction. In order to predict the multiple knife-edge diffraction loss, Bullington's Model, Epstein-Peterson Model and Deygout's Model were introduced. For example, Bullington [11] introduced a nomograph relating signal frequency, height of the obstruction, distance between obstructions to the transmitting and receiving antennas for determining the path loss. Even there are different models available, field measurements must be carried out to validate the model or to adjust the parameters if necessary. For example, Okumura method [12] is based on the data taken in Tokyo area, where Ibrahim-Parsons method [3] was designed for the City of London.

With reference to equation(2.9) and Okumura method, Yacoub [9] stated that supposed the transmitted power, antenna gains, antenna heights and frequencies remain unchanged, then the ratio of the received powers in two points i and j will be given by

$$\frac{W_{rj}}{W_{ri}} = \left(\frac{d_j}{d_i}\right)^{-\alpha} \tag{2.12}$$

or expressed in decibel,

$$10\log\left(\frac{W_{rj}}{W_{ri}}\right) = -\alpha 10\log\left(\frac{d_j}{d_i}\right) \tag{2.13}$$

where W_{ri} and W_{rj} are received powers at points i and j, d_i and d_j are the distances from the transmitting antenna to points i and j respectively. If equation(2.13) is plotted with $10\log(\frac{d_j}{d_i})$ and $10\log(\frac{W_{rj}}{W_{ri}})$ as x and y coordinates, it will be a straight line with slope $-\alpha$. The parameter α is known as the path loss slope. Under free space condition, the path loss slope is $\alpha = 2$ (equation(2.5)), and for flat terrain is $\alpha = 4$ (equation(2.9)).

In case there are regions between the transmitting and receiving antennas with different path loss slope. We will have

$$\frac{W_{r1}}{W_{r0}} = \left(\frac{d_1}{d_0}\right)^{-\alpha_1} \tag{2.14}$$

$$\frac{W_{r2}}{W_{r1}} = \left(\frac{d_2}{d_1}\right)^{-\alpha_2} \tag{2.15}$$

$$\vdots$$

$$\frac{W_{rn}}{W_{rn-1}} = \left(\frac{d_n}{d_{n-1}}\right)^{-\alpha_n} \tag{2.16}$$

Then

$$\frac{W_{rn}}{W_{r0}} = \prod_{i=1}^{n}\left(\frac{d_i}{d_{i-1}}\right)^{-\alpha_i} \tag{2.17}$$

Except the loss due to diffraction, atmosphere also play an important part on creating additional loss. For example, rain will attenuate radio wave significantly with frequency above 10GHz, water vapor will have peak absorption at 24GHz and oxygen will have peak absorption at 60GHz. Moreover, foliage, street orientation and tunnel will have different effect on radio wave propagation. Under indoor condition, we do not need to consider atmospheric and foliage effect because the attenuation due to these two factors inside a particular building will be quite stable. On the other hand, street orientation and tunnel effect can be observed under indoor condition. For example, corridor is the analogue of street at outdoor environment and sometimes corridor will have a tunnel like structure. Jakes [13] stated that in a tunnel, it will have lower attenuation in higher frequency. Yamagouchi *et al* [14] had the same result in their measurement. This argument is just the opposite of Friis free space transmission formula (equation (2.5)). It can tell why the characteristics of radio waves in different frequency bands under indoor condition will highly depend on the shape, the size and structure of the building.

2.1.2 Indoor propagation

Honcharenko *et al* [15] used computer ray tracing for indoor propagation modeling. This model is very accurate but it needs very long time to compute the result. Moreover, The floor plan and the characteristics of all obstructive materials have to be entered precisely before computation. The work will consume a lot of time and manpower. In case there is any unknown parameter or wrong data being entered, the accuracy of computation will be affected.

Harley [16] reported that in his measurement in urban microcell environment, the results were different from that calculated from Okumura model. It showed that a model used in large area outdoor environment will no longer be accurate in microcell environment. Then it can be deduced that models used for indoor environment also differs from those used in large area or microcell environment. For example, all outdoor propagation prediction models consider the obstructions between the transmitter and receiver as objects to creat diffraction loss. It is because those obstructions are large objects like hills, forests or high rise buildings, which are very hard to be penetrated by radio wave. Under indoor environment, the transmitter and receiver may be situated in two different concealed areas, then propagation by diffraction will be impossible. However, the obstructions in indoor environment are comparatively thin which can allow radio wave to penetrate with attenuation of tens of dBs. For outdoor environment, the base station antennas are usually located high above ground level to reduce propagation loss [11]. But for indoor, both transmitting and receiving antennas are usually installed at approximately the same level over the floor. Therefore, different models are necessary for indoor propagation prediction.

Most of the indoor propagation measurement were performed by recording the signal strength of different locations inside the building. The path loss slope can then be found out from a straight line formed by regression of sampled points. By using this method, signal level at all locations inside the building can be found out roughly from the calculated slope. Alexander [17] is one of the first to perform indoor propagation loss measurement. Alexander's later investigation [18] and Arnold *et al* [19] reported that in buildings of different purposes and buildings possessed with different materials, different path loss slopes were measured. However, the accuracy of this method highly depends on the size, shape and materials used in the buildings. Alexander's result [18] showed that the buildings with less obstructions inside had higher accuracy.

In order to prevent the obstructions inside the building introducing higher error, Motley and Keenan [20] proposed the method of deducting the attenuation caused by obstructions from the measured data before calculating the path loss slope where Lafortune and Lecours [21] had similar approach. The relationship among path loss P, path loss slope n and transmitting receiving antennas separation d without obstruction can be shown as

$$P = S + 10n \log_{10} d \tag{2.18}$$

where S is the path loss with 1m antenna separation. If the equation is plotted with $10 \log_{10} d$ and P as the x and y axis respectively, it will be a straight line with slope n and y intercept S.

Equation 2.18 was then modified to introduce the effect of floor attenuation

$$P' + kf = S + 10n \log_{10} d \tag{2.19}$$

where P' is the resulting path loss, k is the number of floors traversed and f is the signal attenuation provided by each floor.

Later Keenan and Motley [22] introduced wall loss in the model, equation (2.19) was modified to be

$$\text{Path Loss} = L(v) + 10n \times \log_{10}(d) + k \times f + p \times w \qquad (2.20)$$

where p and w are the number of walls traversed and attenuation per wall respectively and $L(v)$ is the signal level measure at 1m. Seidel and Rappaport [23] had also measured the attenuation due to different number of floor and effect of wall and partitions.

On the above mentioned reports, the authors calculated the path loss slope with the local mean value of each location without investigated the effect of fading. Hoffman and Cox [24] reported that the received signal envelope was approximately Rayleigh distributed within small area. That means after the measurement or prediction, we have to consider the effect of fading and reserve appropriate margin during system design. Molkdar [25] also reported that the spatial fading rate is much lower in an indoor environment because of the slower motion of the receiver.

French [26] reported that bit error rate can be calculated from the signal levels recorded in field measurement. With the propagation loss prediction model, the bit error rate can also be roughly found out according to different modulation methods. It will greatly reduced the work on field measurement during system design.

2.2 Multipath characteristics

Young and Lacy [27] had conducted one of the first measurements on investigating multipath characteristic in New York City. Short pulses of 450MHz with $0.5\mu s$ duration and repetition rate of $100\mu s$ were sent from the transmitter. The received signal was envelope detected and displayed on an oscilloscope. The waveforms was then recorded by movie camera. Similar method was used later by Saleh and Valenzuela [28] and Rappaport [29]. The differences are only on using higher carrier frequency, shorter pulse duration, higher pulse rate and computer being used as a mean of recording. Envelope detector was still used to retrieve the received pulses. Pseudonoise code of 40Mbits/s had also been used by Devasirvatham [30] to perform the one of the first delay profile measurements in indoor environment.

The radio systems operated in outdoor environment and indoor environment have different multipath delay profile. Molkdar [25] stated that the terrestrial mobile radio systems are usually operated in a relatively open environment and have high transmitting power. The multipath power delay profile usually contains significant signal components at long time delays. In contrast, low transmitting power is usually used in indoor environment. With the effect of building attenuation, signal components with significant levels are improbable. The surroundings and the motion of scatterers in indoor environments have relatively more effects on channel response because of more shadowed transmitting and receiving antennas. Therefore, the multipath power delay profile in an indoor environment is more compact but more susceptible to the surroundings.

Chapter 3

Propagation Model

By reviewing the reports of previous investigations on indoor path loss measurement, Hashemi [31] concluded that there were no universally accepted path loss model available and four distinct path loss models were derived from narrow band continuous wave measurement:

1. The received signal power follows an inverse exponent law with the distance between antennas; i.e., $P(d) = P_0 d^{-n}$, where $P(d)$ is the power received at a distance d from the transmitter and P_0 is the power measured at a distance of 1m. Path loss is proportional to d^{-n}.

2. The received power follows a d^{-n} law as in model 1 but the exponent n changes with distance.

3. This model associates logarithmic attenuations with various types of structure between the transmitting and receiving antennas. Adding these individual attenuations, the total path loss in dB can be calculated.

4. This model associates a dB per unit of distance (antenna separations) path loss within a building.

Model 3 was applied in our measurement to interpret the measured data.

Keenan and Motley [22] reported that the relationship between transmitted and received power for mobile radio application is typically expressed as

$$P_r = P_t - L - 10n \times \log_{10}(d) \tag{3.1}$$

where P_r, P_t, L, d and n are mean received power (dB), transmitted power (dB), clutter loss (dB), separation between transmitting and receiving antennas (m), and path loss slope, respectively. Let $L(v)$ be the mean of the lognormal distributed L with variance v. Equation(3.1) can be written as

$$\text{Path Loss}(dB) = L(v) + 10n \times \log_{10}(d) \tag{3.2}$$

Alexander [18] had conducted a measurement and used a similar equation to analyze the data. It showed that the buildings with less obstructions had higher accuracy. It can be deduced that the equation will work well on the paths with line of sight. If there are floor and wall between the transmitter and receiver, it is more appropriate on considering the effect of the floor and wall. Then Equation(3.2) can be modified as

$$\text{Path Loss} = L(v) + 10n \times \log_{10}(d) + k \times f + p \times w \tag{3.3}$$

where k, f, p and w are number of floors traversed, attenuation per floor, number of walls traversed, and attenuation per wall, respectively.

Before taking data on different locations of different distance, the path loss with one meter between the transmitting and receiving antennas should be first measured to determine $L(v)$. The best fit straight line can be drawn from the data measured within line of sight by regression. Then n, the path loss slope, can be found from equation(3.2). In case there are more data taken with one or more walls but without floor on the path, then by means of those data and the previouly drawn straight line, the difference of path loss between every measured location and the straight line with the same distances can be found and averaged to find out the wall loss w. Then the data taken with walls and floors in between were analyzed by substituting the previously measured $L(v)$ and previously calculated n and w into equation(3.3) to calculate f with the above mentioned method. In case there are more data taken with only floors in between then floor loss f can be calculated first and wall loss w later. If there are not enough data taken at the line of sight positions, n can be set to 2, path loss slope in free space, as suggested by Keenan and Motley [22].

Equation(3.3) can only be applied if both floor and wall in the measured area are each possessed with only one type of material. However, in a commercial building or factory, there may be more than one type of obstructions, for example, the walls may be possessed of different kinds of materials or with different thickness. In this case, equation(3.3) can be modified as

$$\text{Path Loss} = L(v) + 10n \times \log_{10}(d) + \sum_{n=1}^{i} m_n \times o_n \qquad (3.4)$$

where i, m and o are the types of different obstructive object on the path, the number of obstructions with single type of material traversed and attenuation per obstruction, respectively. o_1 to o_i can be calculated one by one with the above mentioned method.

Chapter 4

Measurement Sites and Equipment Setup

Our indoor measurement was conducted in Ho Sin Hang Engineering Building and Postgraduate Hostel. Penetration measurement was done between Ho Sin Hang Engineering Building and Lady Shaw Building. The details of the three buildings and equipment setup are introduced in this chapter.

4.1 Measurement sites

Ho Sin Hang Engineering Building is a ten-story building possessed concrete floors and structure with plasterboard internal partition walls. There are pipes and lights hidden above the false ceiling. The size of the building is 56m by 40m. The measurement was made on the seventh and eighth floor. There is an atrium at the center of the building from eighth floor to sixth floor. Offices and research laboratories are located on every floor. Inside the offices and research laboratories are furniture, desk top computer equipment and small size electronic instruments. The layout is similar to typical office buildings.

The Postgraduate Hostel is a nine-story building possessed concrete floors and structure with brick and concrete walls separating the rooms. There are study-bedrooms at two sides where common rooms, toilets, stair cases and elevator are located at the center of the building. It is an old style building. There is nothing installed under the ceiling except some fluorescent lamps along the corridor. The measurement was done from third floor to fifth floor.

Lady Shaw Building is located nearby Ho Sin Hang Engineering Building and the two buildings are linked by a footbridge. The distance between them is approximately 50m. Lady Shaw Building is a three-story building with two levels of basement. Since the building is located on a slope, the two basements are higher than road level on the side facing Ho Sin Hang Engineering Building. The roof of Lady Shaw Building is approximately at the same level of ninth floor of Ho Sin Hang Engineering Building. The building possessed concrete floors and structure with brick and concrete walls separating the rooms. There is a courtyard located at the center of the building on ground floor. The measurement was performed on second floor and the roof.

4.2 Equipment setup

The instrument setup is shown in Figure 4.1. The setup includes four major instruments:

1. Signal generator

2. Spectrum analyzer

3. Antennas

4. Personal computer

The RF signal generator and spectrum analyzer were used as transmitter and receiver respectively. Each of them was connected to a vertical polarized dipole antenna. The dipole antenna set was designed to operate on a wide bandwidth, therefore the compensation lowered the gain of the antenna to 0dB. The radiation pattern of a vertical polarized dipole antenna is omnidirectional on the horizontal plane. The vertical plane radiation pattern is shown on Figure 4.2 [32]. Each antenna was mounted on a mounting rod which can be rotated 360° on a tripod. The height of both antennas were set to be 1.5m above floor. The noise floor of the spectrum analyzer was lower than -110dBm when span was set at 1kHz. The maximum output level of the signal generator was 16dBm. An additional amplifier could be used to raise the output level up to 22dBm in case of high path loss situation. The measured data from the spectrum analyzer could be stored and sent to a personal computer for processing after measurement. This setup were used on propagation loss, penetration and multipath characteristic measurement.

For propagation loss and penetration measurements, the signal generator was set to send continuous wave. The spectrum analyzer was set to 1kHz span in order to reduce background noise [33]. Before measurement, the signal generator and spectrum analyzer were connected up directly with the antenna feeder cables in order to record the cable loss and calibration difference of the instruments. On every measurement, the distance between antenna mounting rods was first measured and both antennas were rotated with the same angle with

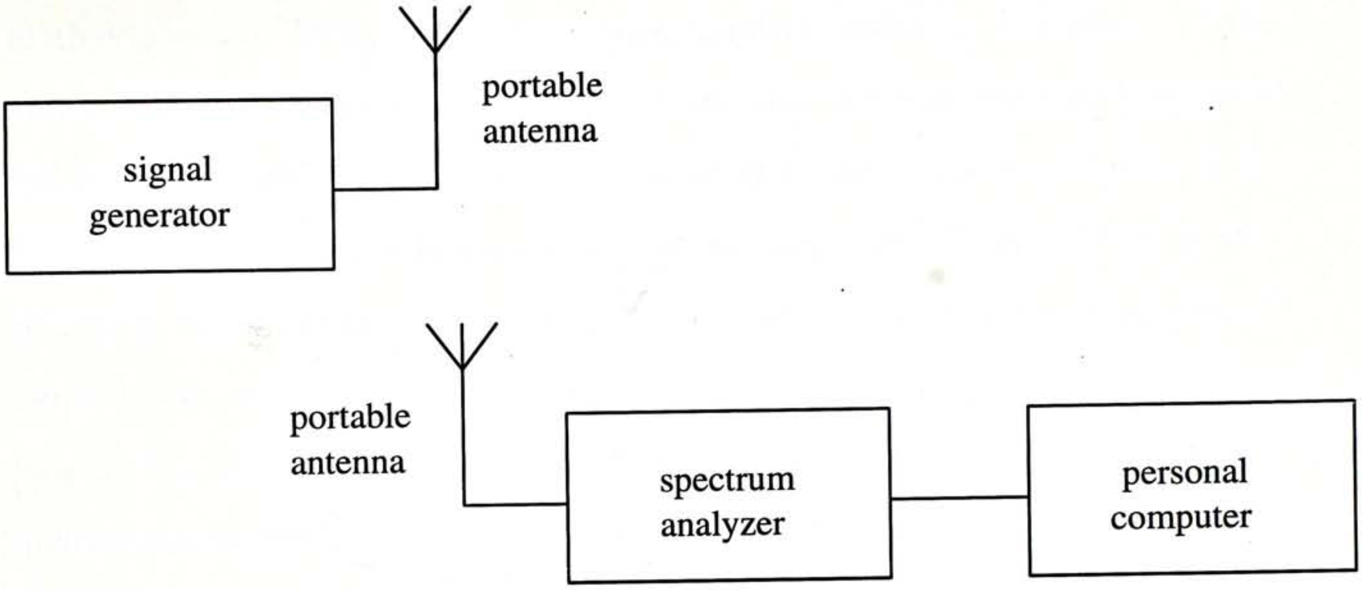


Figure 4.1: Measurement instrument setup

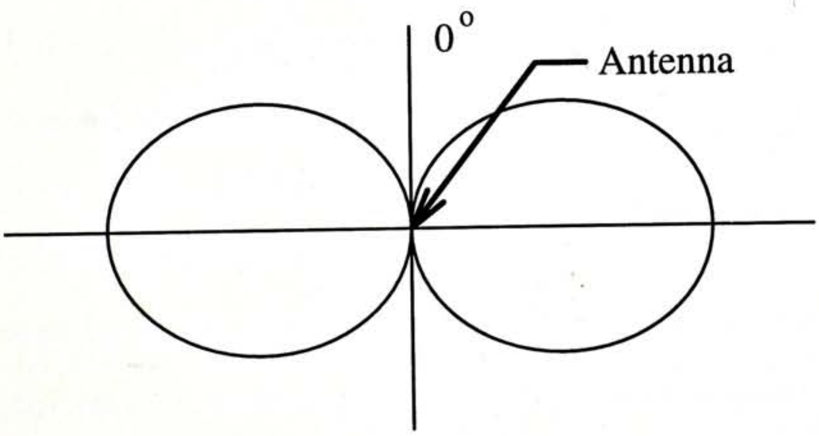


Figure 4.2: Horizontal radiation pattern of a half wavelength vertical dipole

the mounting rod as the axis. The readings at 0°, 90°, 180° and 270° were taken and the mean of these four readings was recorded as the received power level at that position. Path loss of frequencies 250MHz, 400MHz, 800MHz, 1.1GHz and 1.5GHz were measured. The length of the arm of the antenna working from 800MHz to 1.5GHz is 220mm and that for 400MHz and 250MHz is 410mm. Cox [34] stated that under fading environment, received signal levels will be uncorrelated if two antennas are separated further than $\lambda/4$. The measurement of Lemieux [35] even separated the antennas for more than three quarter of wavelength. The arms of the antennas used in our measurement were all longer than quarter wavelength of the measured frequencies. Then the effect on multipath fading could be averaged with the mean received signal level calculated.

The objective of multipath characteristic measurement is to acquire the received signal in time domain [28, 29] but the instrument setup was similar to [36, 37, 38]. The signal generator was sending sine wave which was modulated by a train of pulses with width of 15ns and repetition rate of 600ns. 600ns was chosen because the expected longest delay would not exceed 600ns, then overlapping of received pulses was not likely to exist. The span of spectrum analyzer was set at 250MHz. Multipath characteristics of 800MHz, 1.1GHz and 1.5GHz were measured. The spectrum of each measured signal in digital form were stored in the memory of the spectrum analyzer in 401 samples. The spectrum was then converted to matrix form, and the center frequency was shifted from the carrier frequency to zero. In order to smooth the noise and have a higher time domain resolution, 1000 more samples were added on both sides of the 401 samples with the level set arbitrarily as the same as the noise floor. Total 2401 samples were then converted to time domain by Inverse Fast Fourier Transform

(IFFT) software on a standalone computer or workstation. The method was similar to that used by Hashemi [39]. The time domain waveform was reconstructed by taking the modulus of the inverse Fourier transformed samples. This method can have the similar result of using a fixed tuned receiver and envelope detector as [28, 29].

In a big city, it is usually very hard to find a frequency band of several hundred megahertz without interference. If interference does exist, no matter what method is used to remove the unwanted signal, the waveform will definitely distorted. By using such method, the interference can be removed by software before applying IFFT. It can prevent using expensive and bulky notch filters. The procedure on frequency domain and time domain transformation is more complicated than the method of using network analyzer as on [36, 37, 38] and also the phase information is unable to be measured by a spectrum analyzer. However, by using signal generator and spectrum analyzer instead of a network analyzer, the transmitting and receiving antennas can be located at further separated or even isolated positions. Hence the length of the antenna feeder cable will no longer limit the choice on antenna locations.

The antennas used in the multipath characteristic measurement were also half wavelength dipoles. In some previous multipath characteristic measurements, for example, Rappaport [29] and Saleh and Valenzuela [28], discone antennas were used. Discone antenna has an advantage of very high bandwidth [40, 41, 42] but the measurements of Howard and Pahlavan [36, 37] did not show excessive roll off at the edge of the measured frequency band by using dipole. Since discone antenna is not available, dipole was used instead.

Chapter 5

Measurement Results

In this chapter, the results of measurements performed in Ho Sin Hang Engineering Building and Postgraduate Hostel are presented in terms of propagation loss due to floors and walls. Results on measurement of penetration loss at the atrium of Ho Sin Hang Engineering Building and Lady Shaw Building as well as results from wideband transmission are also presented.

5.1 Propagation loss in the same building

Propagation loss measurement was done in Ho Sin Hang Engineering Building [43] and Postgraduate Hostel. The internal layout as well as materials used for internal partition of the two buildings are different. In this section, the propagation loss model was examined by data acquired in these two buildings.

5.1.1 Measurement in Engineering Building

Figure 5.1 shows the floor plan of eighth floor, Ho Sin Hang Engineering Building, where the floor plan of seventh floor is similar. At first, measurement was done at corridor C. The path loss slope and mean square error calculated from the measured data are shown in Table 5.1. In the measurement, the separation between transmitting and receiving antennas ranged from 1m to 20m. The antennas were located with equal distance between the walls on both sides. All points measured were in line of sight. The path loss slope for all frequencies except 250MHz were below 2. It showed the waveguide effect [28], and also showed that 250MHz and 400MHz decayed faster than the higher frequencies.

The path loss slope and mean square error calculated from data measured in room A are shown in Table 5.2. The distance between transmitting and receiving antennas ranged from 1m to 7m. All points measured were in line of sight and no obstruction higher than one meter above floor level. The path loss slope was also below 2 and 250MHz also had a high rate. When the transmitting and receiving antennas were too close, the received signal level was greatly affected by the antenna radiation pattern [32, 44]. It resulted as a low path loss slope. Therefore, this set of data could not be use as reference to determine the wall and floor attenuation factors.

Throughout the measurement of determining the wall and floor loss, the transmitting antenna was located in room B closed to the window. The receiving antenna was then moved around at the western side of the building on eighth and seventh floors. Since there is an atrium located at the center of the building, data taken at eastern side of the building are likely to be affected by reflected or diffracted paths and will be more difficult to be analyzed. Signal level were measured at the locations with different number of wall between the transmitter and receiver. Data were also taken at the locations on seventh floor to examine the effect of floor. Without applying wall and floor factors, the path loss slopes calculated are shown in Table 5.3. The path loss slopes of the five frequencies were around 5 and the mean-square error figures were high. It had the similar results as Seidel and Rappaport [23]. Since the rooms on eighth floor are not large enough to prevent the influence from antenna radiation pattern, therefore, there were not enough positions to measure the signal level with both antennas in line of sight. Then after applying floor and wall correction, the free space path loss slope was used as in [22]. The floor attenuation factor was found by averaging the path loss at several locations in room B and corridor C with the transmitting antenna on eighth floor and the receiving antenna directly below on seventh floor. Those locations were selected because there were no other significant path other than penetrating the floor. The wall effect was calculated by averaging the difference between all data with floor attenuation deducted and the straight line Path Loss $= L(v) + 20\log_{10}(d)$. In order to minimize the mean square error, the signal levels at all locations with wall and floor attenuation deducted were used to construct a new best-fit line with slope 2 to find out a new $L(v)$. After the floor and wall attenuation introduced, the results are shown in Table 5.4. On Figure 5.2, the points marked with 'x' indicate the measured signal levels, and the points marked with '+' indicate the signal levels with wall and floor attenuation deducted. It indicated better confidence in signal level predication. It also showed that except 250MHz, $L(v)$ of all frequencies had values higher than the measured ones. Since the separation between transmitting and receiving antennas of all measured positions were less than 50m, it did not showed obvious break points as in [15, 44]. However, because there is an atrium located at the center of the building, part of the transmitted energy would propagate across the atrium via the reflected path instead of the direct path, then the error could not be further minimized.

When the path loss at corridor C was measured, both the transmitting and receiving antennas had been moved round the corners at both ends of the corridor to examine the effect of the corners on propagation loss. The loss increased ranged from 20dB to 30dB on the five frequencies when both antennas were located one meter from the corner. With reference to the wall attenuation shown in Table 5.4, it showed that the path of penetrating through the walls dominated and the effect of the diffracted path was not obvious. The path loss started to decrease while the antennas were further moved towards the atrium. It indicated that the path with reflection on the wall at eastern side of the atrium dominated and resulted as enhancing the signal level.

5.1.2 Measurement in Hostel

Figure 5.3 shows the floor plan of third floor, Postgraduate Hostel, where fourth and fifth floors had similar floor plan. It is an old style building where no pipe and conduit was installed under the ceiling. The method of measurement was the same as that of Engineering Building. The path loss slopes shown in Table 5.5 were calculated from the data measured at corridor D with separation between transmitting and receiving antennas ranged from 1m to 20m. 250MHz also had the highest path loss slope and mean square error. The path loss slopes of 400MHz, 800MHz and 1.5GHz were all between 1 and 2. The performance of the four frequencies except 1.1GHz was similar to that of Engineering Building. The path loss slope of 1.1GHz was only 0.98. The height of the corridor was found to be 2.73m, exactly ten times of wavelength of 1.1GHz. On top of that, the smooth surfaces of the ceiling, walls and floor made the corridor behaved like a waveguide.

Since the internal walls in the hostel have two different thickness, therefore, floor, thick wall and thin wall attenuation factors were introduced. It indicated better confidence in signal level predication from the results shown on Tables 5.6 and 5.7.

There is an elevator in the hostel which affected the measurement at the western end of the building. When the receiving antenna was located at the elevator lobby, the elevator shaft was situated right on the propagation path. Since the elevator was moving frequently, then other obstructions on the path such as cable, balance weight and elevator door would be moving consequently. None of them has the same attenuation factor and it was impossible for us to shut down the only elevator in the building. Therefore, the data taken at that area were not used on calculation. It resulted that the furthest transmitting and receiving antennas separation was only 10.8m. The measurement in room A of Engineering Building and [44] showed that when the transmitter and receiver separation was below 10m, the path loss slope would be lower than 2. However, the results of Postgraduate Hostel did not show a high error. It was expected that the high attenuation of the walls and floor on the propagation path eliminated the effect on the antenna radiation pattern.

5.2 Penetration across the atrium and neighboring building

Penetration across the atrium was measured on eighth floor of Engineering Building by locating the transmitting antenna in room A and the receiving antenna at D on the opposite side of the atrium as shown in Figure 5.1. The measurement was done with both window-shades pulled up and lowered on both side of the atrium. The receiver was then moved to seventh floor directly below position D to measure the floor effect. The results are shown in Table 5.8. For 400MHz and 800MHz, the path loss with window-shade pulled up were higher than that of window-shade lowered. It is expected that the metallic window-shade acted as an antenna element which enhanced the gain of the dipole antenna. The results measured at seventh floor showed that except 400MHz and 800MHz, the path loss measured were similar to that of eighth floor. Since the receiver was in line of sight, therefore the floor did not have significant effect on path loss. The receiving antenna locating at the null of multipath fading might be the reason of path loss of 400MHz and 800MHz at the eighth floor being higher then the others.

Penetration to the building further apart was examined with the receiving antenna located at different positions in Lady Shaw Building and the transmitting antenna located on eighth floor of Engineering Building as shown in Figure 5.5. Most of the data were taken on second floor of Lady Shaw Building, which is at the same level as the eighth floor of Engineering Building. Data measured are shown in Table 5.9. Apart from 800MHz, the results indicated that higher frequency had higher path loss. Same as before, the window-shade did not introduced high extra loss except 250MHz. Location R is at line of sight, locations A, B, C and D are not. There are two walls between the transmitting antenna and the receiving antenna for locations A and B and four walls for locations C and

D. However, the data measured at C and D did not show the high attenuation of the walls. It is because C and D are at the side the courtyard and radio wave could diffract and eliminated the effect of the walls.

5.3 Multipath characteristics

The measurement was done at corridor C in Engineering Building. The transmitting and receiving antennas were 3m apart. The measured waveforms in time domain with 800MHz, 1.1GHz and 1.5GHz are shown in Figure 5.6. The waveforms of 800MHz and 1.1GHz showed some spatial correlation on the starting 30ns. The two peaks followed the main pulse were found to be echo from the walls on both side and also from the floor and ceiling. The signal level died out quickly after that and hardly found the reflection from both ends of the corridor. Since the transmitted power was low and it decayed quickly after bounced back from the end of the corridor.

The 1.5GHz waveform did not correlated with the other two waveforms. It is expected that shorter wavelengths are easier to be interfered by the irregular shaped surfaces.

Using spectrum analyzer and software for multipath characteristic measurement has a limitation on the area of the site. Since the spectrum analyzer has to be set to wide dispersion, it results as high noise floor of about -70dBm. At the same time, the transmitter only transmits for 1/40 of the whole period. The pulses bounced back from the objects far away may be masked by the background noise. However, the setup of instruments is simpler then the other methods. This shortcoming can be corrected by using higher transmitter output power.

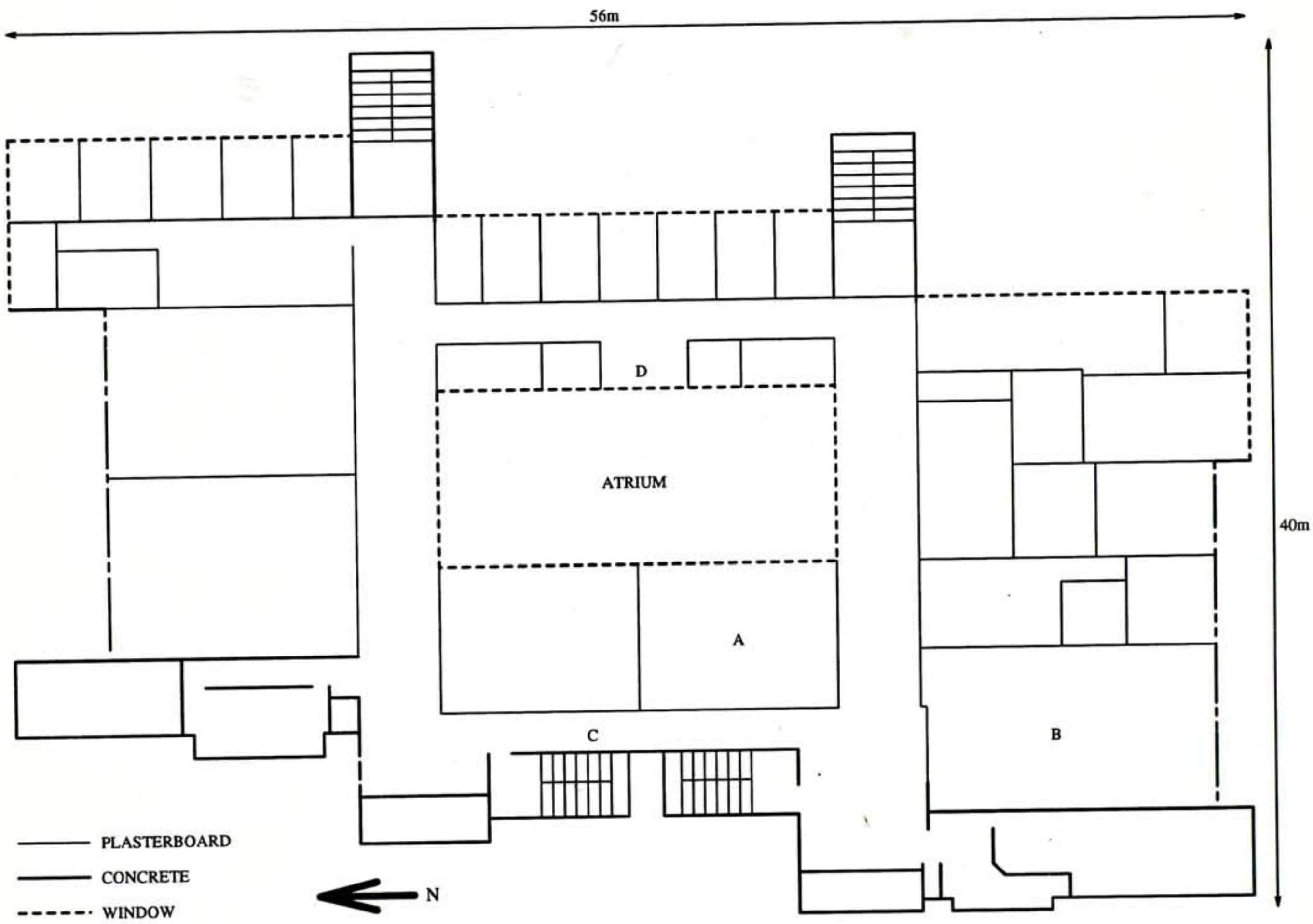


Figure 5.1: Floor plan of eighth floor, Engineering Building

Table 5.1: Results calculated from data measured in corridor C.

	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	2.15	1.76	1.56	1.40	1.48
MSE	15.97	7.56	8.64	4.50	1.06

Table 5.2: Results calculated from data measured in room A.

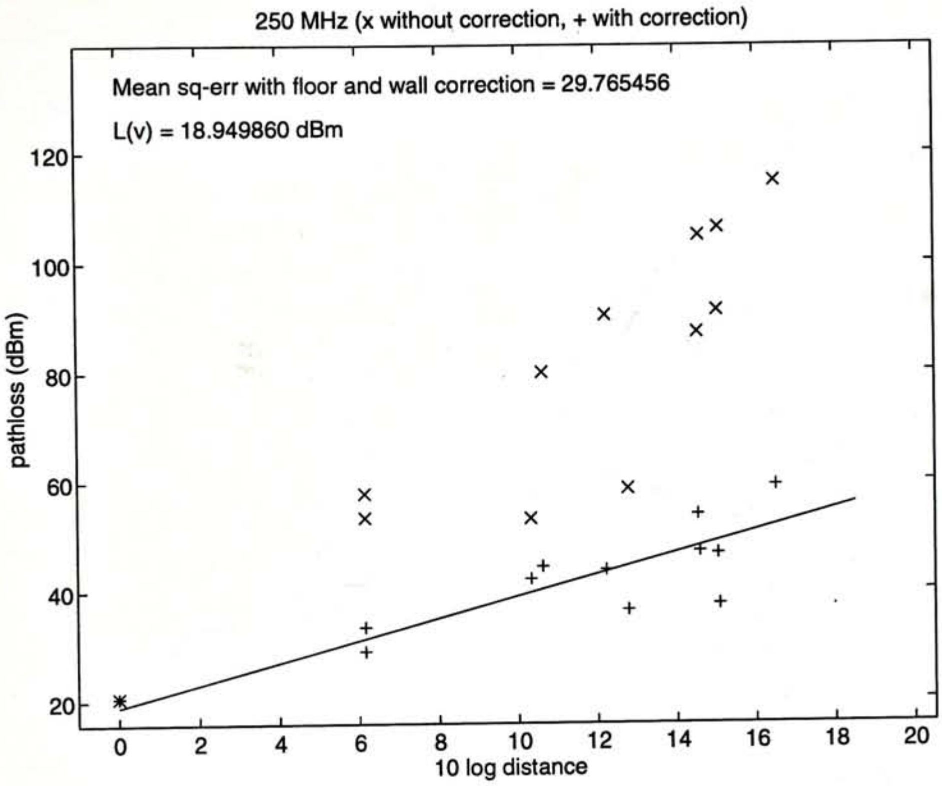
	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	1.66	1.57	1.42	1.67	1.51
MSE	1.13	0.72	7.67	2.99	6.85

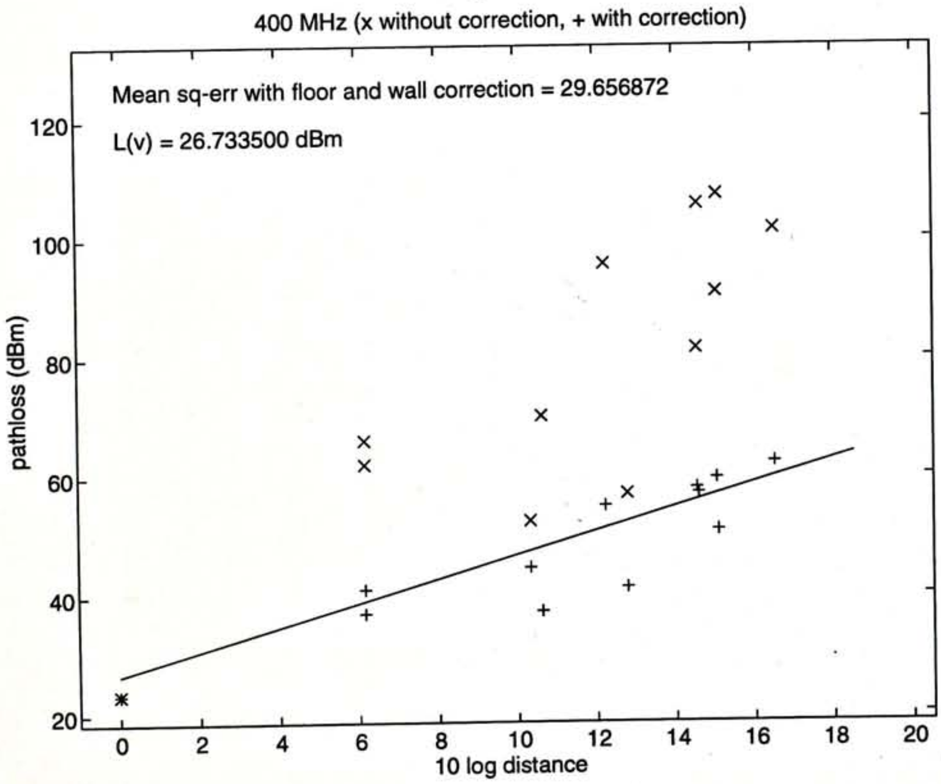
Table 5.3: Results calculated from data measured in western side of the building on seventh and eighth floor, without floor and wall correction.

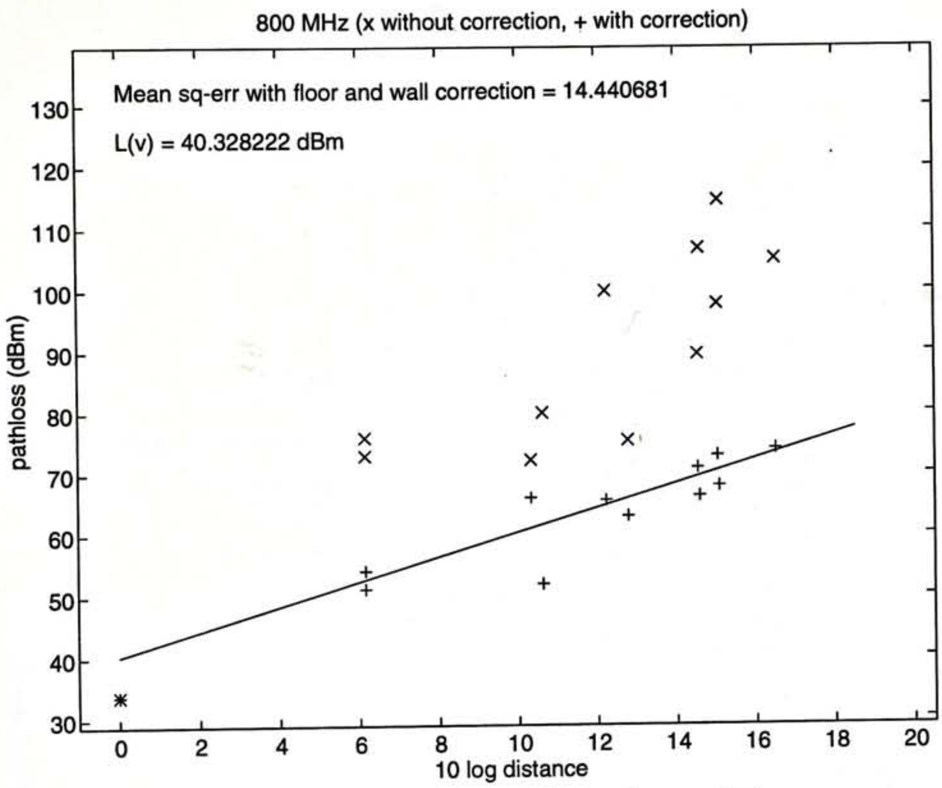
	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	5.03	4.68	4.52	4.68	4.68
MSE	147.16	188.57	101.66	108.86	145.73

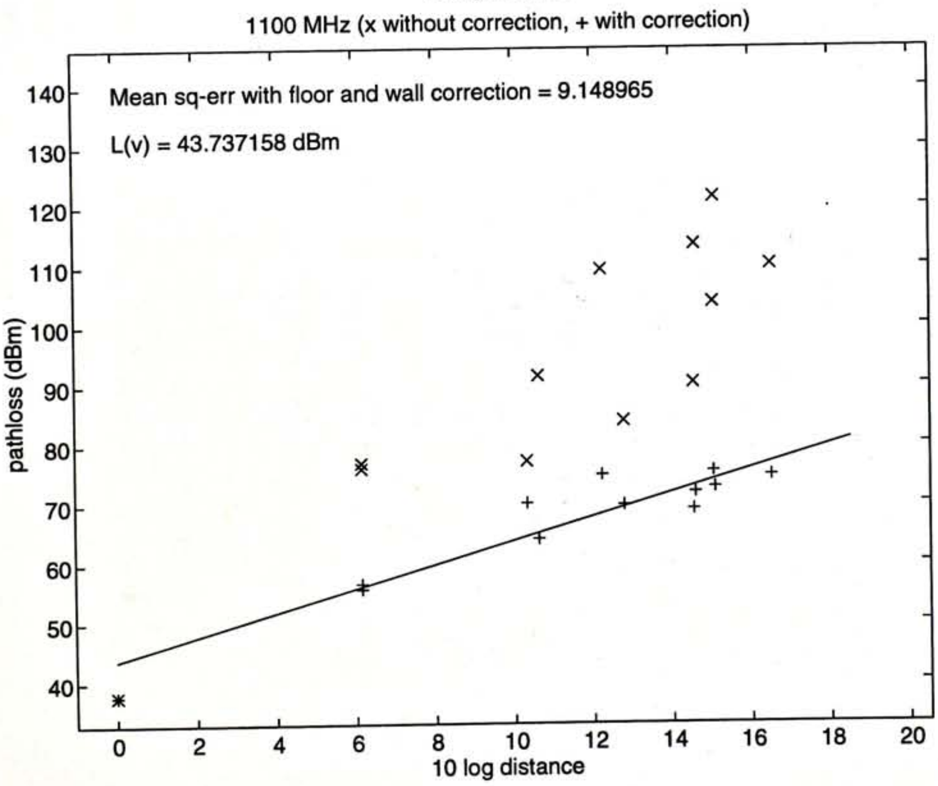
Table 5.4: Results calculated from data measured in western side of the building on seventh and eighth floor, with floor and wall correction.

	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	2	2	2	2	2
MSE	29.77	29.66	14.44	9.15	16.95
floor attenuation factor (dB)	22.76	28.42	28.33	26.42	26.42
wall attenuation factor (dB)	10.81	8.44	7.51	8.23	8.32
L(v) (dB)	18.95	26.73	40.33	43.74	46.35


250 MHz (x without correction, + with correction)
Mean sq-err with floor and wall correction = 29.765456
L(v) = 18.949860 dBm
pathloss (dBm)
10 log distance


400 MHz (x without correction, + with correction)
Mean sq-err with floor and wall correction = 29.656872
L(v) = 26.733500 dBm
pathloss (dBm)
10 log distance


800 MHz (x without correction, + with correction)
Mean sq-err with floor and wall correction = 14.440681
L(v) = 40.328222 dBm
pathloss (dBm)
10 log distance


1100 MHz (x without correction, + with correction)
Mean sq-err with floor and wall correction = 9.148965
L(v) = 43.737158 dBm
pathloss (dBm)
10 log distance

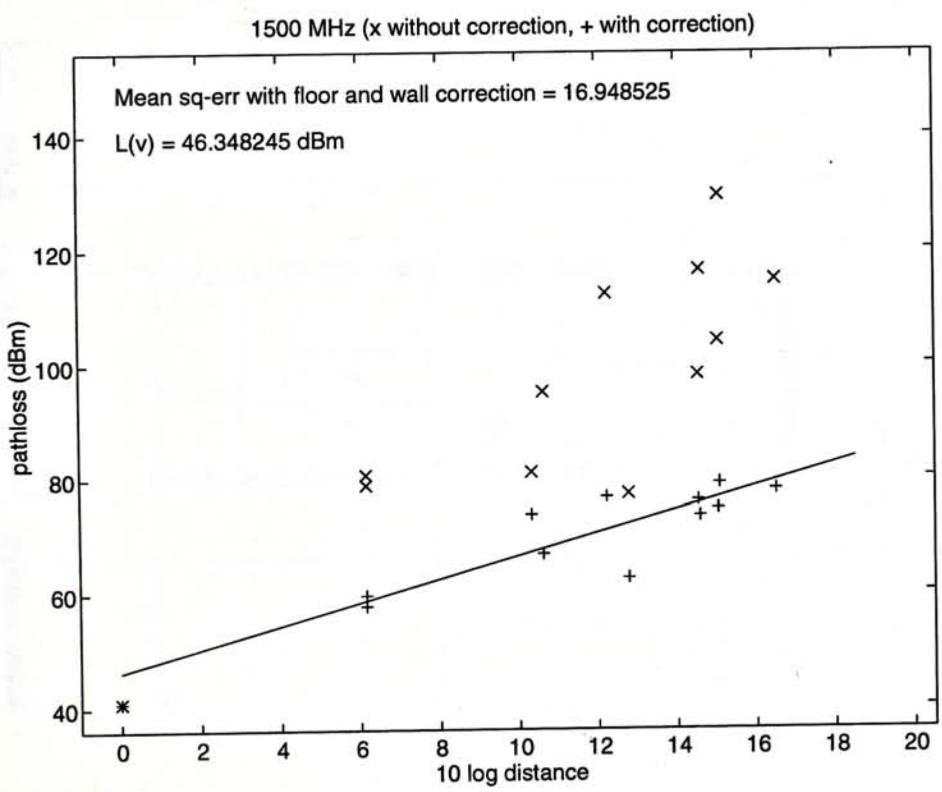


Figure 5.2: Measurement results with wall and floor correction

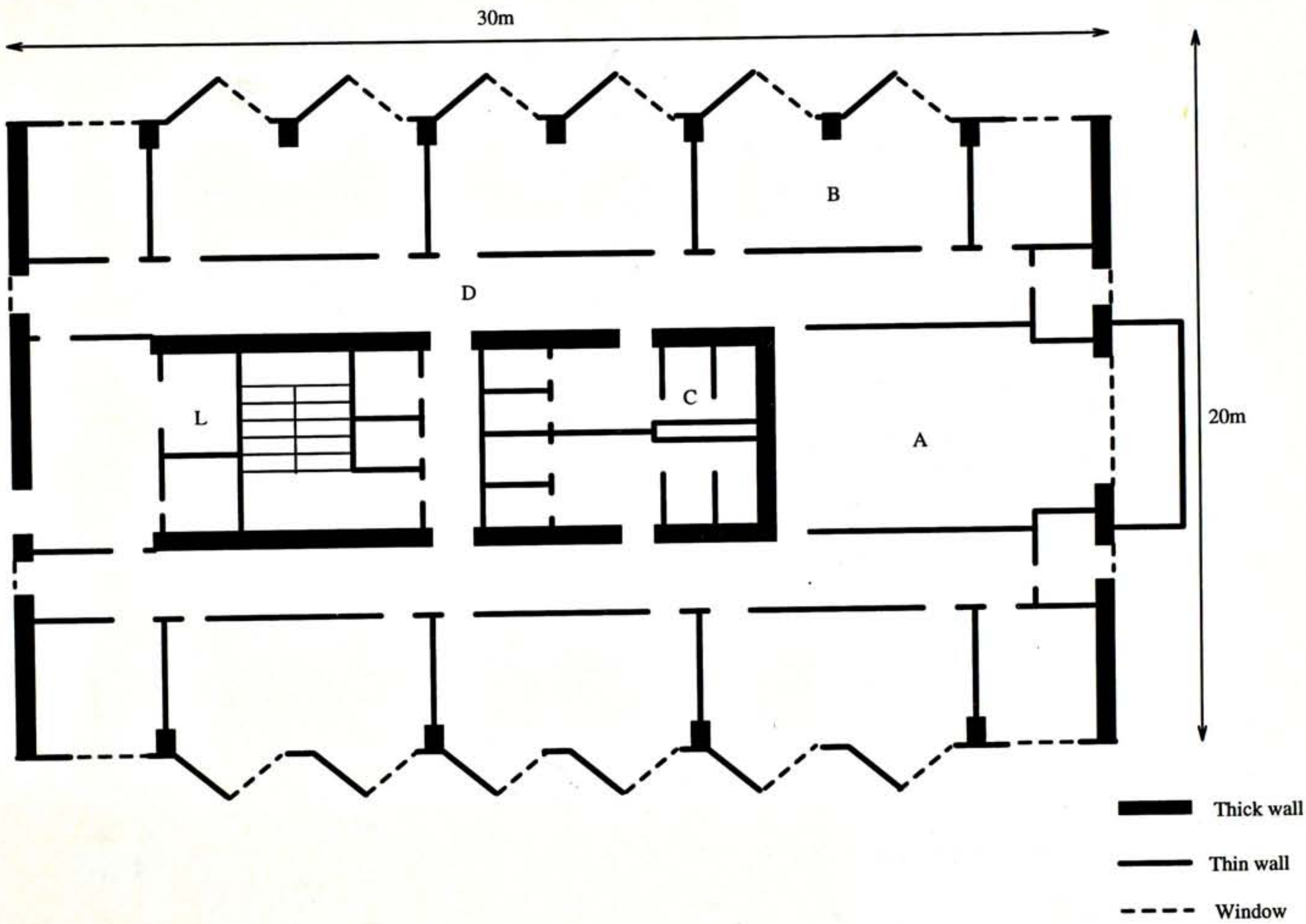


Figure 5.3: Floor plan of third floor, Postgraduate Hostel

Table 5.5: Results calculated from data measured in corridor D.

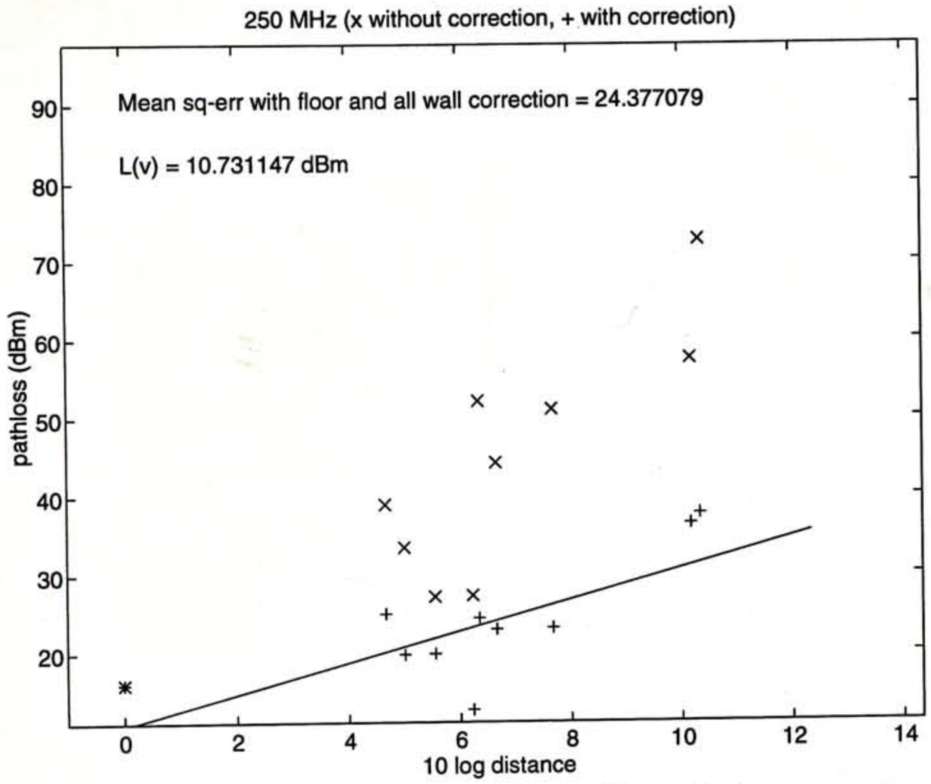
	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	3.20	1.37	1.69	0.98	1.27
MSE	32.02	6.29	7.89	1.14	2.23

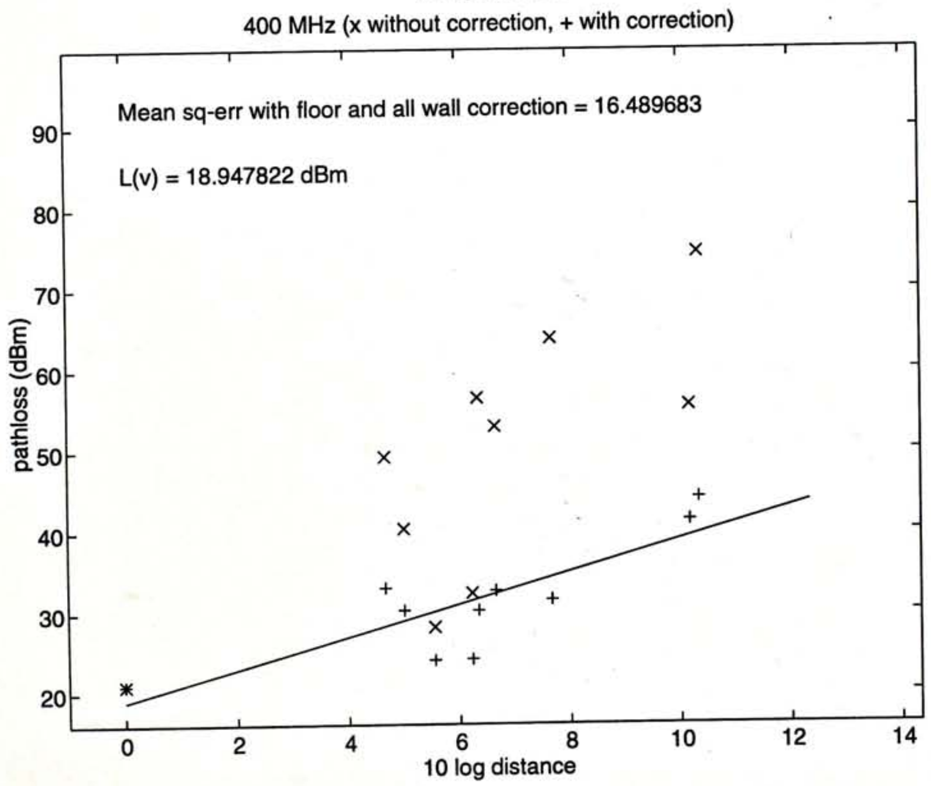
Table 5.6: Results calculated from data measured in the hostel on third, fourth and fifth floor, without floor and wall correction.

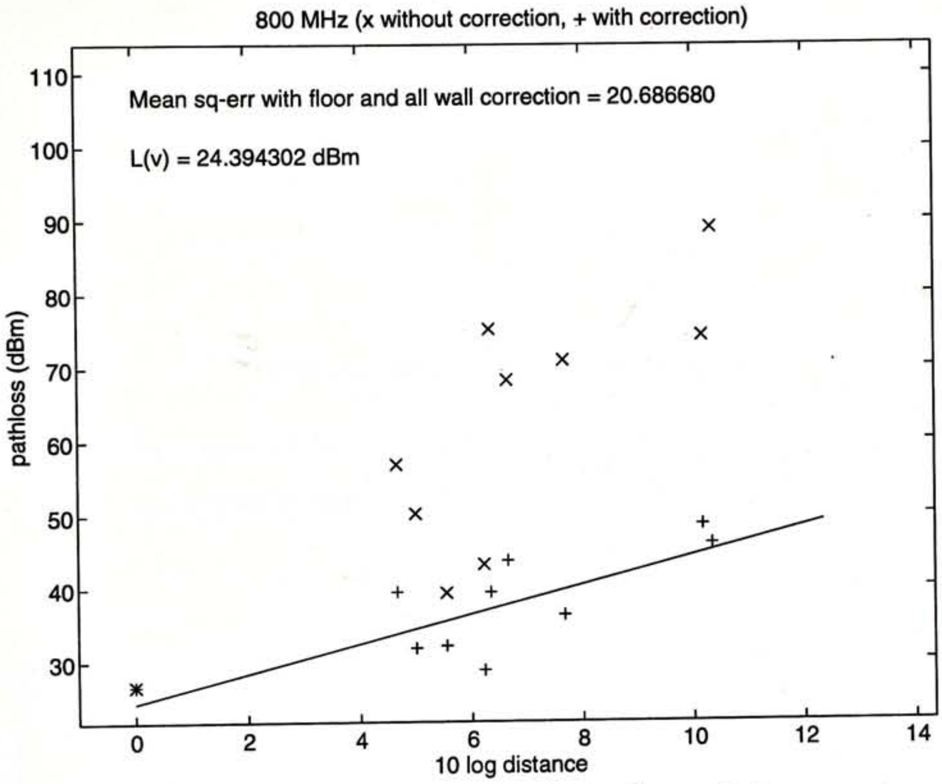
	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	4.99	4.55	5.58	5.68	5.60
MSE	61.77	92.63	95.01	112.69	166.08

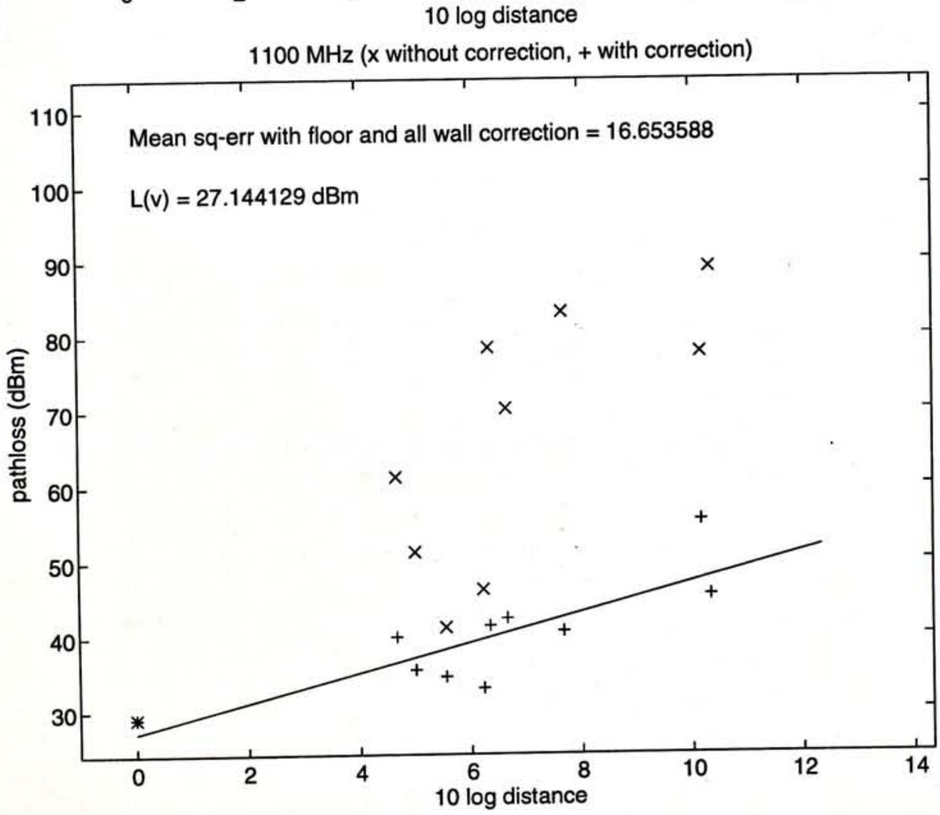
Table 5.7: Results calculated from data measured in the hostel on third, fourth and fifth floor, with floor and wall correction.

	Carrier Frequency (MHz)				
	250	400	800	1,100	1,500
slope	2	2	2	2	2
MSE	24.38	16.49	20.69	16.65	10.58
floor attenuation factor (dB)	13.98	16.21	17.33	21.28	19.47
thick wall attenuation factor (dB)	13.71	10.10	18.37	15.76	22.32
thin wall attenuation factor (dB)	7.31	4.12	7.23	6.627	3.26
L(v) (dB)	10.73	18.95	24.39	27.14	32.94


250 MHz (x without correction, + with correction)
Mean sq-err with floor and all wall correction = 24.377079
L(v) = 10.731147 dBm
pathloss (dBm)
10 log distance
90
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14


400 MHz (x without correction, + with correction)
Mean sq-err with floor and all wall correction = 16.489683
L(v) = 18.947822 dBm
pathloss (dBm)
10 log distance
90
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14


800 MHz (x without correction, + with correction)
Mean sq-err with floor and all wall correction = 20.686680
L(v) = 24.394302 dBm
pathloss (dBm)
10 log distance
110
100
90
80
70
60
50
40
30
0
2
4
6
8
10
12
14


1100 MHz (x without correction, + with correction)
Mean sq-err with floor and all wall correction = 16.653588
L(v) = 27.144129 dBm
pathloss (dBm)
10 log distance
110
100
90
80
70
60
50
40
30
0
2
4
6
8
10
12
14

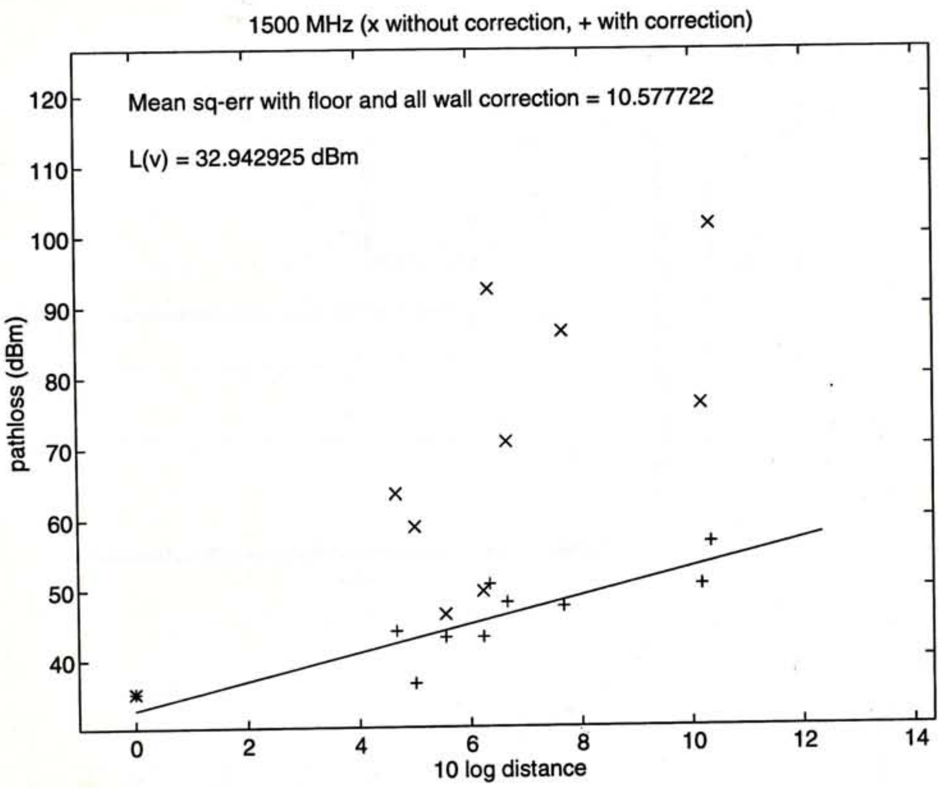


Figure 5.4: Measurement results with wall and floor correction

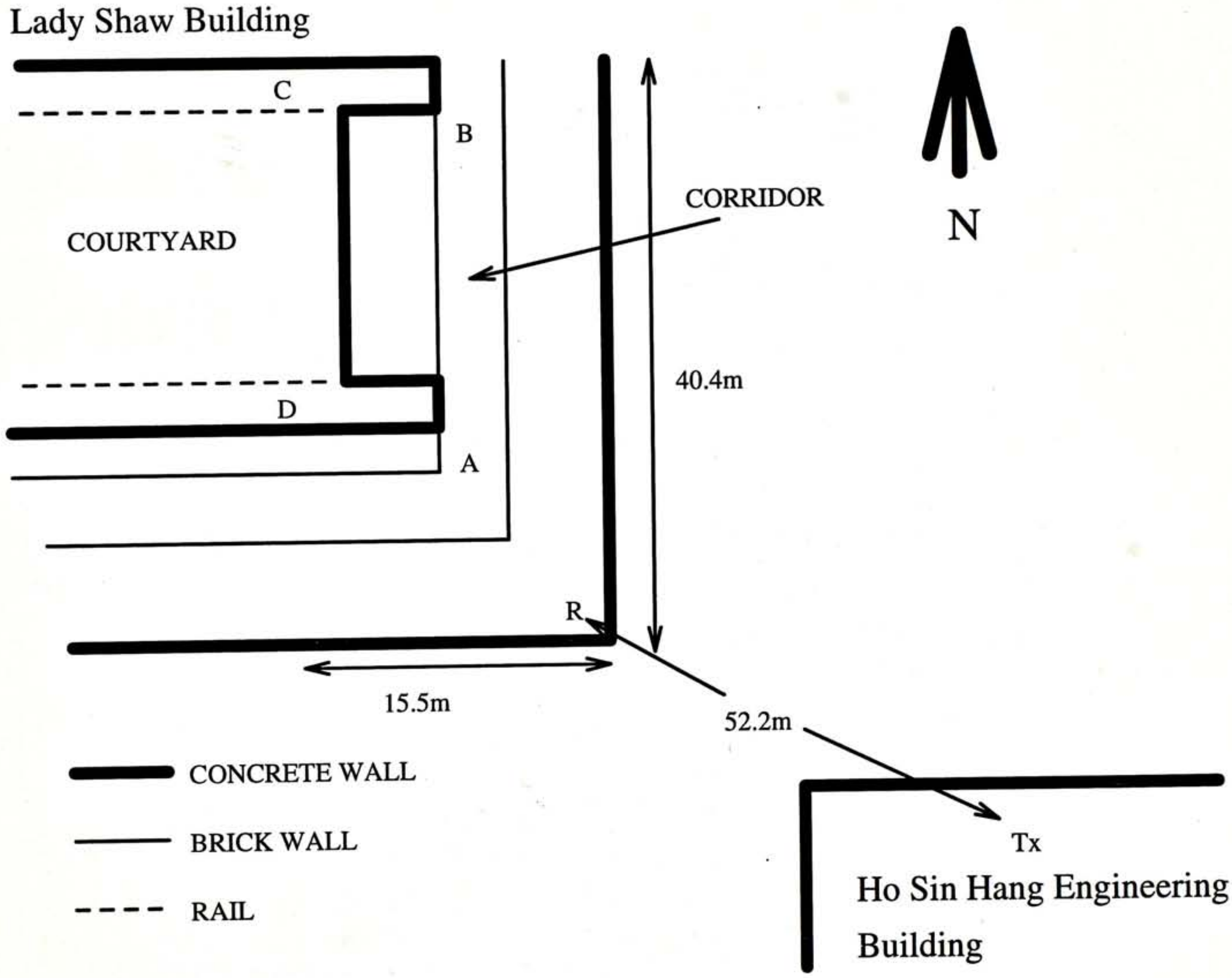


Figure 5.5: Locations of the transmitter and receiver on penetration measurement between Ho Sin Hang Engineering Building and Lady Shaw Building

Table 5.8: Path loss in dB measured across the atrium at Ho Sin Hang Engineering Building.

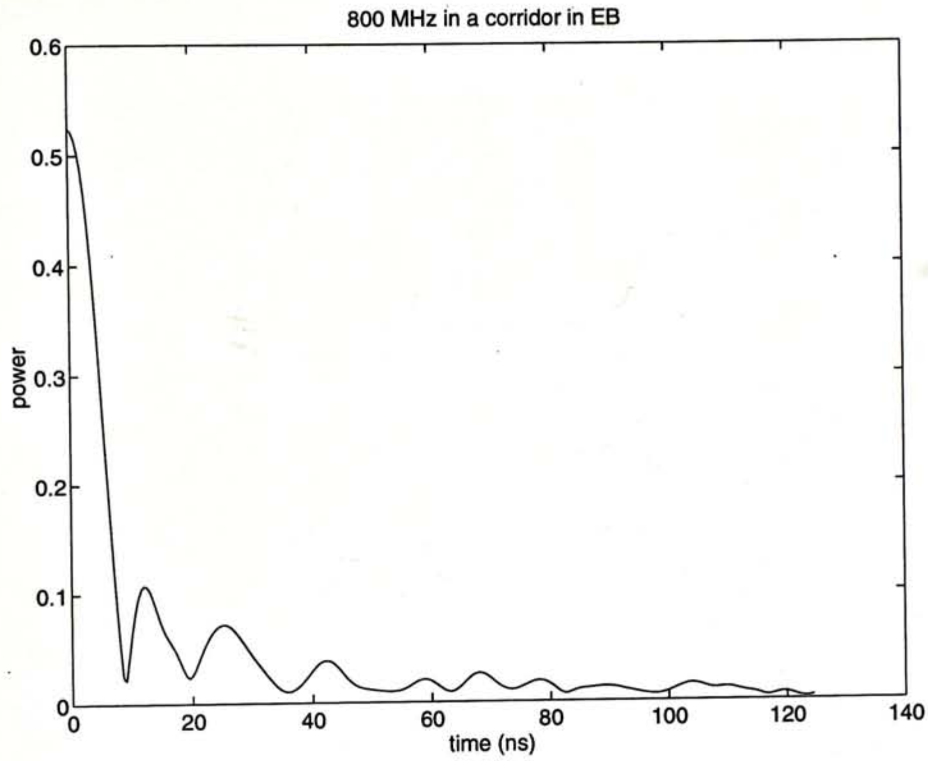
	Carrier Frequency (MHz)					
Locations	250	400	800	1,100	1,500	d (m)
A	42.59	37.75	44.76	54.71	67.30	10.6
B	41.33	38.76	47.76	52.52	59.76	10.6
C	42.26	46.45	50.76	54.09	66.68	11.4

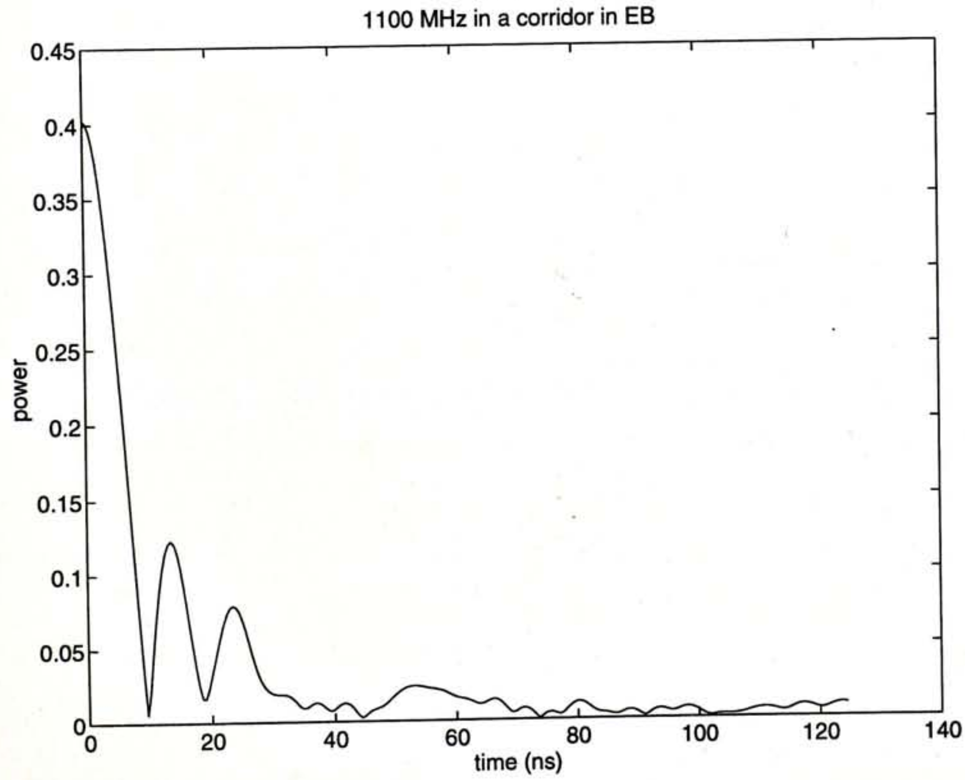
A: 8/F across atrium with shade.
B: 8/F across atrium without shade.
C: 7/F across atrium with shade.
d: distance.

Table 5.9: Path loss in dB measured between Ho Sin Hang Engineering Building and Lady Shaw Building.

	Carrier Frequency (MHz)					
Locations	250	400	800	1,100	1,500	d (m)
R	61.25	62.29	75.38	69.19	76.29	52.5
A	83.25	79.03	82.30	92.11	90.43	63.3
B w/o s	77.50	87.98	86.95	92.24	97.41	91
B w s	85.84	85.39	85.93	91.13	98.21	91
C	88.29	88.16	96.41	102.90	99.28	97.5
D	97.59	94.70	103.98	105.15	100.675	70

d: distance.
w/o s: without shade.
w s: with shade.


800 MHz in a corridor in EB
power
time (ns)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
20
40
60
80
100
120
140


1100 MHz in a corridor in EB
power
time (ns)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0
20
40
60
80
100
120
140

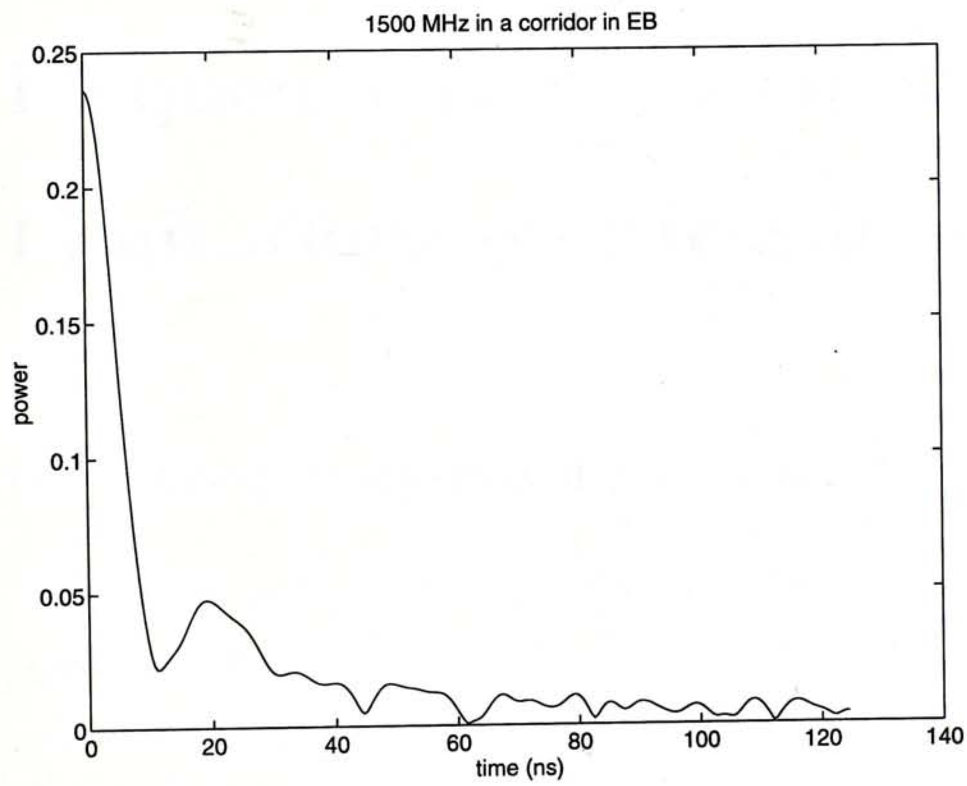


Figure 5.6: Multipath waveforms measured in Engineering Building

Chapter 6

Frequency Reuse Planning and Limitations on Measurement

6.1 Frequency reuse planning

The results of path loss measurement show that walls have significant effect on signal attenuation. If the base station is located at the center of the building, signal can reach any part of the floor by passing through minimum number of walls and can have better coverage on the same floor. It can also keep the base station away from neighboring buildings to reduce interference. Even though the floor has high attenuation on radio wave, if there is a building situated beside then that building will behave as a reflector and radio wave will bounce back to the other floors in the same building [45]. It is clearly shown by the result at location D of Lady Shaw Building.

If 10mW transmitter output power is used, in order to have a reliable communication link, an indoor cell should not cover more than three floors with the base station located on the middle floor. By carefully locating the base station antenna, the path loss to the receiver with four floors separated would easily exceed 100dB. Honcharenko *et al* [46] showed that diffraction loss was lower than floor loss when there are four or more floors separating the transmitter and receiver, such that power propagated via diffraction path would be dominated. It can explain why the floor attenuation will decrease as number of floor increases as reported by Seidel and Rappaport [23]. However, the transmitter output power in his experiment was 1.61W, 22dB higher than our transmitter output power. In our measurement, the received power would be too low before diffraction became significant. Therefore, using two sets of frequencies will be enough for a building. However, the neighboring buildings should use different sets of frequencies.

If the base station antenna has to be installed nearby a window with metallic window-shade, special care should be taken to prevent unwanted signal penetrating the neighboring buildings. Since the window-shade will not attenuate signal very much, it will sometimes enhanced the antenna gain instead.

It is undesirable to locate an indoor radio communication system base station antenna on the roof. With reference to the result at location R of Lady Shaw Building, the transmitter will cover the neighboring building successfully but the floor attenuation will limit its coverage at the same building.

Except on floor penetration, 250MHz is the frequency with the worst performance, this band should not be chosen in indoor radio system if other alternatives are possible. According to the results, the other frequencies did not differed much in performance.

With reference to some previous works on indoor path loss measurement, Yamagouchi *et al* [14] reported that in a tunnel, higher frequency had lower attenuation. In contrast, Motley and Keenan [20] had a result of higher frequency had higher attenuation in a building. This contradiction is expected to be caused by the clearance between the floor and the ceiling, the size and shape of the building. The results of our measurement at the corridor in the hostel showed that 1.1GHz had the lowest attenuation. It may be due to the smoothness of the ceiling and the clearance being exactly the multiple of the wavelength. From the corridor measurement in the Engineering Building, no frequency had extremely low attenuation. It is because there are pipes installed above the false ceiling then the roughness of the ceiling caused the corridor to introduce high attenuation. It can be concluded that in indoor environment, the path loss will not drop or rise monotonously by following the frequency. On the other hands, the results of penetration measurement performed between Engineering Building and Lady Shaw Building showed that under outdoor environment, the path loss rose with frequency increasing.

The measurement of Yamagouchi *et al* [47] showed that the tunnel with pedestrian inside would have less path loss. The frequencies used in their measurement were from 250MHz to 12.4GHz. However, Macario [48] showed that when a pager was carried on the waist, the antenna radiation pattern will be approximately omnidirectional in 150MHz but that of 900MHz showed high attenuation on the body side. The reasons of causing this contradiction may be on operation environment and antenna characteristics. The attenuation on human body may change in different situations and frequencies, so this factor should be considered carefully to avoid unpredictable black area to exist or excessive interference to cochannel cells nearby.

6.2 Limitations on the propagation loss measurement

It was shown by Yacoub [9] that the outdoor path loss prediction models will not perform satisfactorily under every possible condition. Indoor propagation prediction has the same problem. The propagation loss prediction model stated in Chapter 3 can only be used to study the attenuation on a direct path. If significant diffraction or reflection path exists, the accuracy of the model will be greatly reduced and it tends to overestimate the propagation loss.

In our measurement, in order to prevent interfering the existing radio communication systems, the transmitter output power was limited to 10mW. With such low power, signal can only penetrate two floors. Therefore, the effect on diffraction, which will be significant with four floors separating the transmitter and receiver [46], was unable to be measured with such setup. This can only be examined if transmitter of higher output power is allowed to be used.

There is an atrium at the center of the seventh and eighth floors in the Engineering Building. If the transmitter and receiver were located nearby two opposite sides of the atrium, the radio wave will not only penetrate through the walls along the direct path, it will also propagate along the reflected or diffracted paths and those paths may be significant. Under such situation, if the signal level received is abnormally high, the floor plan should be studied carefully before taking the data on wall and floor attenuation calculation. In our measurement, this is the reason why the data were only taken at the western part of the Engineering Building to calculate the floor and wall loss factors.

6.3 Limitations on multipath measurement

In order to prevent the received pulses with longer delay coincide with the next transmitted pulse, the transmitter had to be set to send pulse on every 600ns. With pulse duration of 15ns, the average power of the transmitted signal is very low. Moreover, the wide dispersion of the spectrum analyzer raised the noise floor. When the distance between transmitter and receiver is too large, the received signal will be masked by the background noise. Therefore, in the multipath measurement, the distance between transmitter and receiver was only 3m. If the measured area is larger, a power amplifier should be used to raise the transmitted power to acquire reliable data.

Chapter 7

Conclusions

With the measurement performed in Engineering Building, models of calculating path loss on 250MHz, 400MHz, 800MHz, 1.1GHz and 1.5GHz were evolved. The model was verified with the measurement in the Postgraduate Hostel and proved that it could be applied to another buildings without excessive error. The effects of wall, floor, corridor and metallic window-shade were studied. With different transmitter locations, penetration to Lady Shaw Buildings was measured. Frequency reuse planning can be done by using the measured results. Multipath characteristics was also measured by using spectrum analyzer and IFFT software. It demonstrated an alternate method of doing such measurement in small area and with short transmitter to receiver separation. Even there are limitations on the methods used on measurements, with appropriate transmitter and receiver locations, the limitations can be eliminated to minimum.

Appendix A

Method of Calculating Path Loss Slope

On Figure A.1, a straight line $y = b + ax$ is formed from regression of sampled points [49]. Assumed that there are a set of data $A_i(x_i, y_i)$ $(i = 1, \ldots M)$ and the y intercept b recorded from experiment. Those known values can be used to construct the best-fit straight line, then a, the slope of the straight line, can be found. With the parameters a and b, the calculated values $y(i) = ax_i + b$ can also be found.

Since the best-fit line will not go exactly through each data point $A_i(x_i, y_i)$, therefore the residuals $\varepsilon_i = y_i - (ax_i + b)$ can be considered as a measure of the error. The least-squares criterion requires minimizing

$$m(a, b) = \sum_{i=1}^{M} \varepsilon_i^2 = \sum_{i=1}^{M} [y_i - (ax_i + b)]^2 \quad \text{(A.1)}$$

When this method is applied to the path loss measurement, x-axis is $10 \log_{10} d$ and y-axis is the received signal level in dB, where d is the separation between transmitting and receiving antennas in meter, y_1 to y_M are the signal levels measured at M different locations, x_1 to x_M are ten times the logarithm of the transmitting and receiving antennas separating distances of those locations, b is the signal level measured with 1m antenna separation and a is the path loss slope, the parameter we want to find out from the measurement.

In order to minimize m for constructing the best-fit line, we have to let $\partial m/\partial a = 0$.

$$\frac{\partial m}{\partial a} = \sum_{i=1}^{M}[2x_i^2 a - 2x_i y_i + 2bx_i] = 0 \tag{A.2}$$

$$a\sum_{i=1}^{M} x_i^2 - \sum_{i=1}^{M} x_i y_i + b\sum_{i=1}^{M} x_i = 0 \tag{A.3}$$

$$a = \frac{\sum_{i=1}^{M} x_i y_i - b\sum_{i=1}^{M} x_i}{\sum_{i=1}^{M} x_i^2} \tag{A.4}$$

$$a = \frac{\sum_{i=1}^{M} x_i(y_i - b)}{\sum_{i=1}^{M} x_i^2} \tag{A.5}$$

Then the path loss slope can be found from the recorded data.

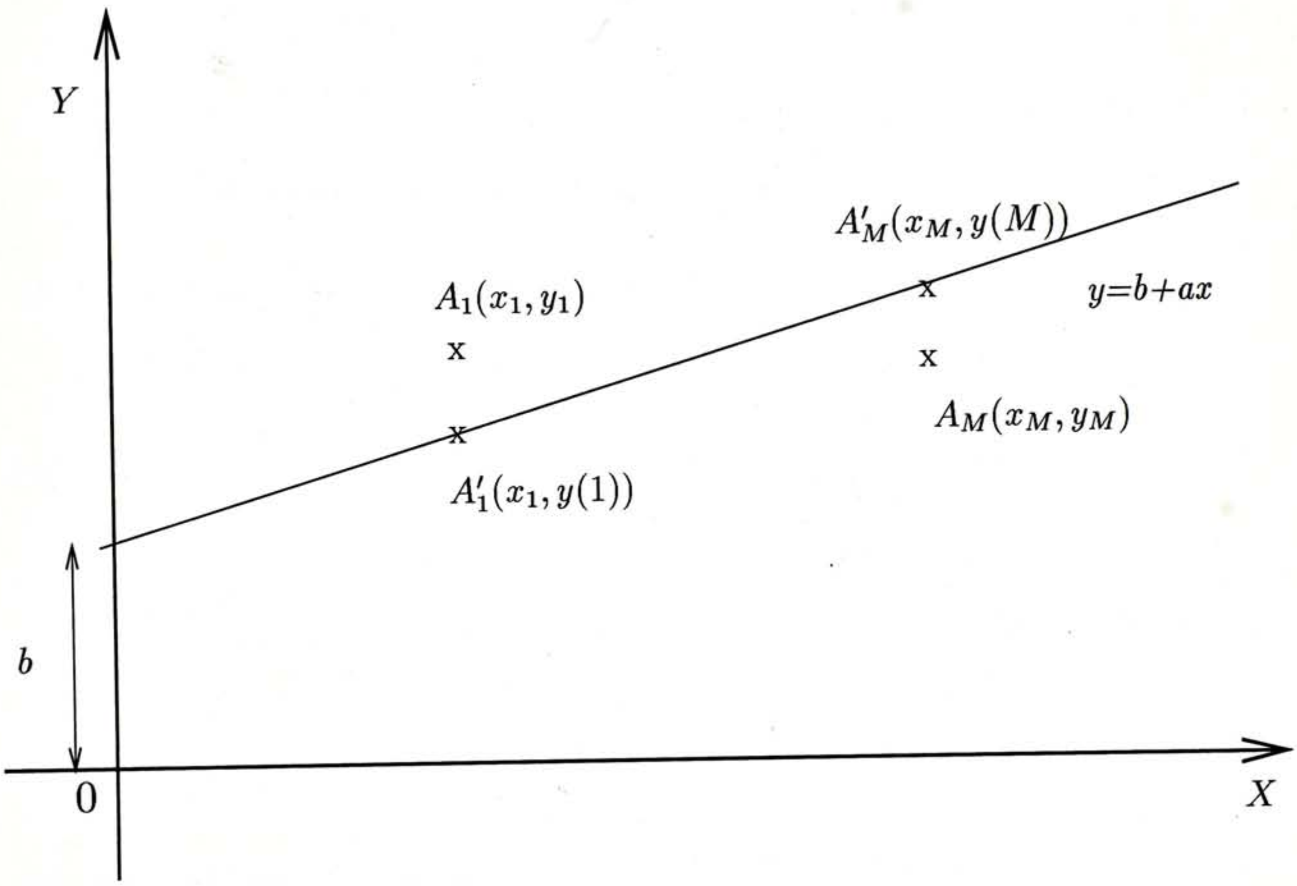


Figure A.1: A straight line formed from regression of sampled points

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