Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

# Empirical Outdoor-to-Indoor Propagation Path Loss Models Investigation and Tuning for 900, 1800 & 2100 MHz Frequencies: the Case of Addis Ababa City

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Approval by Board of Examiners

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# Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

Zerihun Teshome ______________

Name Signature

Place: Addis Ababa

Date of Submission: _______________

This thesis has been submitted for examination with my approval as a university advisor.

Dr. -Ing. Dereje Hailemariam ______________

Advisor's Name Signature

# Abstract

As trend of cellular traffic shifts from voice dominant to data and most of this traffic is being generated from indoor environment, providing optimal indoor solutions is becoming prime target of a radio planning task. But, it is a challenging task to meet the radio signal coverage target that ensures signal quality required by data traffic in indoor environment as radio propagation is impacted by building penetration loss (BPL) and in building propagation path loss. Hence, to ensure radio signal coverage target in such environment it is required to closely investigate and characterize these two losses.

Investigating and characterizing these losses is prominently important for vertically expanding cities like Addis Ababa, Ethiopia, where outdoor macro sites are predominant solution to avail indoor environment signal coverage targets. This thesis aims to accomplish this critical task for city of Addis Ababa.

Representative sample buildings based on morphology, purpose, building material types and building to transmitter antenna height relation are selected. Moreover, commonly used indoor propagation models are identified. Measurement is undertaken, based on measurement it is attempted to estimate BPL and tuned model parameters for the selected propagation models for various categories of indoor environments to determine unified outdoor-to-indoor propagation model.

The results indicate that for a frequency of 900MHz, BPL for buildings made from hollow concrete blocks/bricks is identified as 12.01dB to 17.7dB; for building made from stone masonry the value ranges from 15.11dB to 17.81dB; and from 2.46dB to 8.81dB for buildings mainly made from glass. For 1800MHz frequency the identified BPL results are: 13.7dB to 17.51dB for buildings made from hollow concrete blocks/bricks; 16.38dB to 25.41dB for buildings made from stone masonry; and 0.89dB to 8.14dB for buildings mainly made from glass. Similarly, BPL for 2100MHz frequency is identified as 12.22dB to 13.36dB for buildings made from hollow concrete blocks/bricks; 14.16dB to 19..66dB for buildings made from stone masonry; and 6.25dB to 10.36dB for buildings mainly made from glass. Then, for the measured indoor path loss, parameters of the Path Loss Slope (PLS) model were tuned to capture radio signal propagation characteristics in the indoor environments. The results indicate that, the path loss exponent is found out to be in the range of 0.52 to 2.09 depending on the indoor environment considered. To validate the models, Root Mean Square Error (RMSE) is computed and it is found out it ranges from 1.06dB to 5.25dB depending on different building environments and selected models.

The resulting outdoor-to-indoor propagation models can be used for coverage planning in the city of Addis Ababa.

**Key Words**: *Building penetration loss; Path loss Outdoor-to-indoor models; Tuning*

# Acknowledgement

After passing through significant challenges this thesis work comes to an end. I have to pause here and pass my heart felt gratitude to those who have supported me to complete this journey successfully.

I like to express my heart felt gratitude to Dr._Ing. Dereje Hailemariam, my advisor in thesis work, for his continuous follow up and close support from the beginning all the way to the end of the research work. This thesis work wouldn't be a reality without his support and follow up.

I like to thank G/Medhin, Bizuayehu, Belete, Sefefe, Kalkidan and Belayhun from ethio telecom Engineering Department who supported me by participating in the measurement campaign; as well as availing measurement and analysis tools.

One of the challenges of indoor measurements is getting the required level of access to the building premises. Hence, I like to pass my gratitude to building owners who have supported me by giving access privilege to their building premises to conduct the necessary measurement. Hats off to all!

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# Acronyms

| | |
|---|---|
| 3G | Third generation mobile network |
| 5G | Fifth generation mobile network |
| BPL | Building penetration loss |
| DAS | Distributed antenna system |
| EDGE | Enhanced data rate for GSM evolution |
| eMBB | Enhanced mobile broadband |
| GSM | Global system for mobile |
| HSPA | High speed packet access |
| HSPA+ | High speed packet access plus |
| LOS | Line-of-site |
| LTE | Long-term evolution |
| LTE-A | Long-term evolution -advanced |
| mMTC | Massive machine type communications |
| mmWave | Millimeter wave |
| NLOS | Non-line- of-site |
| PLS | Path loss slope |
| PL | Path loss |
| QoS | Quality-of- service |
| RMSE | Root mean square error |
| RSCP | Received signal code power |
| RSRP | Reference signal received power |
| RSRQ | Reference signal received quality |
| SHO | Soft handover |
| SSE | Sum of squares of the errors |
| URLLC | Ultra-reliable and low-latency communication |
| WCDMA | Wideband code division multiple access |
| Wi-Fi | Wireless fidelity |

# Chapter 1

# 1. Introduction

According to [1] mobile subscriptions are growing at around 4 percent year-on-year, reaching 7.9 billion in 2018 quarter one (Q1). On other hand mobile broadband subscription are growing by around 20 percent year-on-year and the total number of mobile broad band subscription has been around 5.5 billion in 2018 Q1 worldwide.

If we consider Long Term Evolution (LTE) as an example to show the data growth, the subscription continues to grow strongly globally, added 210 million new subscriptions in 2018 Q1 only to reach 2.9 billion subscribers. During this period Wideband Code Division Multiple Access (WCDMA)/High Speed Packet Access (HSPA) added 10 million new subscriptions while subscription of Global System for Mobile (GSM)/ Enhanced Data rate for GSM Evolution (EDGE) declined by 90 million subscriptions. It is expected that LTE subscription will keep growing and reach 5.5 billion by 2023. Even though it has been estimated that WCDMA/HSPA subscription will decline, one fifth of global mobile subscribers will be still on WCDMA/HSPA by the same year. Major operators in North America have already announced to start 5G rollout by the end of 2018 and start of 2019 and it is expected operators in Japan, South Korea and China will follow. It has been forecasted that there will be 1 billion 5G subscription by 2023 [1].

In Ethiopia HSPA+ and 3G subscription has already reached 15.6 Million and LTE subscription has reached 0.241 Million and the total number of cellular data subscribers have reached 15.65 Million by the end of 2017. Both HSPA Plus (HSPA+) and LTE-

Advanced (LTE-A) will be the dominant wireless broadband solution for few more years to come and number of cellular data subscribers will increase by three fold[4].

While the capacity of HSPA+, LTE and 5G network continues to grow, majority of the cellular data network users are located inside buildings where coverage is difficult to insure because of high penetration losses [5]. By 2015 over 80% of mobile usage was inside buildings and predicted to increase to above 90% in the subsequent few years [6]. If this huge volume of traffic is not planned, deployed and managed properly it will have big impact on the operator quality of service, churn rate of subscriber will increase and eventually revenue of the operator will significantly be reduced. In the case of ethio telecom, significant indoor 3G data service quality problem in Addis Ababa has already been encountered [26].

Generally mobile traffic has already shifted from voice dominant to data and majority of the data traffic is generated from indoor. Hence characterization and modeling of into and in building radio propagation path loss is very critical task.

Before starting investigation, analysis and modeling of radio propagation path loss, it is required to select radio frequencies to be studied. Frequency band for specific cellular network deployment is selected based on the operating environment (outdoor and/or indoor), required coverage and capacity targets, and available spectrum. Globally the most frequently used frequency bands for LTE deployment are 1800 MHz and 2600 MHz, 800 MHz have been also widely used [3]. 2100 MHz & 900 MHz have been widely used for WCDMA/HSPA+ deployment. 5G is expected to use the current LTE frequency bands and frequency in millimeter bands. In Ethiopia 1800MHz has been used for LTE deployment. In cities 2100 MHz and in towns and rural areas 900 MHz has been used for UMTS/HSPA+ deployment while 1800 and 900MHz is being used for GSM/EDGE. Hence, it is possible to observe that 900MHz, 1800MHz and 2100MHz are the most commonly used frequencies both in Ethiopia and globally for cellular network deployment.

## 1.1. Problem statement

Cellular indoor data traffic is impacted by the coverage target set to ensure the minimum signal quality that maintains voice service which used to be the dominant cellular traffic. However, this coverage target is no more enough for data service as data service demands more resource and signal quality. Indoor quality of service, coverage and capacity are further impacted by the following factors [6]:

- Modern mobile devices have to support a wide range of frequency bands in a small form factor, reducing their sensitivity and hence increasing the signal strength needed to achieve given coverage which leads to additional loss of 5dB to 8dB
- Improved thermal insulation properties of buildings lead to an increase in the use of denser and more conductive external construction materials, including metallized windows, increasing the losses which radio waves encounter in penetrating a building which lead to additional loss of 9dB
- Increased use of high-frequency bands which suffer greater losses than frequencies below 1 GHz and hence may introduce more radio shadow areas

In the specific case of ethio telecom, key buildings in Addis Ababa were surveyed by Engineering Department of ethio telecom to identify the level of signal coverage problem and address customer complaint. As indicated in the Figure1.1, in some of those buildings considerable amount of building area has not been covered at all or covered with signal strength below required level that is -95dBm[26]. This is mainly due to the fact that while selecting and planning wireless broadband solutions such as HSPA+ and LTE and their operating frequency bands, the indoor environment has not been investigated at adequate level. Specifically outdoor–to- indoor and indoor radio propagation path loss characteristics and models, which are very important inputs for optimal indoor coverage and capacity planning has not been studied and used.

In the network planning and dimensioning exercises, a generally set building penetration loss (typically 10dBm) margin which is not adjusted based on commonly used building materials in the city has been used.

Hence it worth an effort to investigate outdoor-to- indoor and in building radio propagation path loss characteristics of the commonly used frequency bands, to identify and optimize appropriate propagation models.

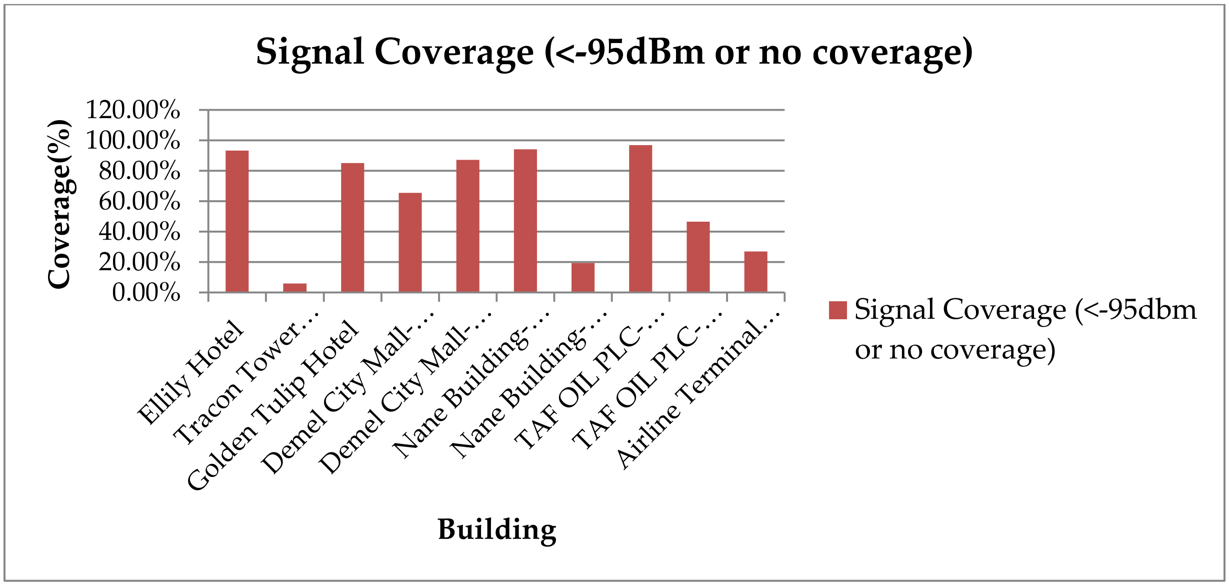


Figure 1.1.Sample buildings signal coverage in Addis Ababa dense urban & urban areas.

## 1.2. Objective

### 1.2.1. General objective

In this thesis it is intended to determine building penetration losses (BPL) for various building types via measurement for commonly used frequency bands (900MHz, 1800MHz and 2100MHz) and then identify optimal outdoor-to-indoor propagation models that characterizes the indoor environment in the city of Addis Ababa.

### 1.2.2. Specific objective

In this thesis it is considered that the total outdoor-to- indoor propagation path loss is consisted of outdoor path loss, building external walls penetration loss and in building path loss and each of them can be studied and identified separately and combined to give the total outdoor-to-indoor propagation path loss. Following this approach the specific targets indicated below will be realized.

- Select buildings based on predefined criteria and undertake measurements.
- Investigate and determine building material dependency of BPL for 900, 1800 and 2100 MHz
- Investigate and determine frequency dependency of BPL.
- Observe and report building height dependency of path loss for 900, 1800 and 2100MHz.
- Determine BPL by categorizing the investigated buildings into few major groups based on the material they are made from.
- Suggest outdoor-to-indoor propagation model as combination of the outdoor propagation model and the identified BPL for less conservative outdoor macro sites to indoor coverage planning.

- Compare log- normal shadowing and path loss slope (PLS) propagation models against the measured results (focusing on 1800MHz).
- Tune the model parameters to improve the models and suggest better performing propagation model.

## 1.3. Literature review

In the effort to meaningfully understand indoor propagation characteristics several studies have been conducted in the areas of BPL, outdoor- to- indoor, indoor, and indoor- to- outdoor propagation characteristics. These studies have covered from broadcast to millimeter frequency bands, from residential houses to large office buildings made from different variety of materials under different transmission conditions such as none line of site ( NLOS), partial line of site and Line of Site (LOS). These studies usually tried to investigate impact of frequency, building material and building structure, building height, transmission conditions (LOS &NLOS) and signal grazing angles on the propagation characteristics. Most of the studies were conducted to devise some sort of propagation models from measured data [7][8][9][10][12][17].

Several research works which had been dedicated to identifying building entry penetration loss were done. While some of the research works try to investigate and separate out building entry penetration loss, others report the average room, or floor loss as building penetration loss.

In [7] radio signal propagation losses is investigated focusing on identifying loss experienced by radio signal while entering or leaving building and impact of different building materials on these losses. In this paper frequency range from 100MHz to 6GHz was covered. Detail survey of building material types and their electrical characteristics, especially the impact of insulation materials used to conserve energy, was undertaken. It has been found that the radio signal loss depends on frequency, signal incident angle and building material and the signal loss increases wherever insulation materials has been used. In this paper, even if it has been tried to separate building entry penetration loss and internal penetration loss, it is difficult to conclude the identified building entry loss is entirely because of the external wall as measurements were taken at references points up to 3m in to the building.

In [8] Jan-Eric Berg from Ericsson Radio System had investigated penetration loss of 1700MHz radio signal from microcells along Stockholm down town street for a building with external wall made from bricks and reinforced concrete. In this research work BPL of 30 to 55dBm was identified. But this penetration loss is the average of entire penetration loss of a given room. In another work by similar researcher building penetration model had been developed for frequency range of 800-2000MHz using values from free space path loss model as outdoor reference signal instead of those outdoor reference signals from measurement [9]. Penetration loss for external wall made from concrete was 4 to 10dB while for wood it had been 4dB .For perpendicular incident angle 5 to 10dB and for small grazing angles 25 to 30 dB penetration loss was reported.

In most of the reviewed literatures outdoor macro sites have been rarely used as source of radio signal to investigate building entry losses. In [13] using macro green field sites as source of radio signal BPL for four buildings made from bricks and concrete masonry was studied. The operating frequency of the macro sites were 850MHz and 1900MHz. The reported mean penetration loss was 9.5dB to 14.6dB with standard deviation from 4.16dB to 4.7dB for 850MHz and 11.1dB to 17.2dB with standard deviation 1.5dB to

2.07dB for 1900MHz. In this paper it had been observed that for some of the building the penetration loss increases with frequency and for others the loss is independent of frequency. Average floor gains of 0.58dB/m had been also observed. But in this research covered only those buildings in a campus located in sub urban area and height of all the buildings was less than that of antenna height of the macro BTS sites. Besides the reported penetration less is the average penetration loss of entire room.

Similarly in [10] roof top located test transmitters had been used as signal source and buildings with large open areas and corridors were investigated in detail. BPL of 14.83dB to 21.40dB had been witnessed for 900, 1800 and 2300MHz frequency bands. In this work it was observed that penetration loss decreases with increasing frequency.

The study that was conducted in typical sub urban Nigeria using live GSM network revealed that building mad from concrete, blocks and muds have average penetration loss of 10.62dB, 4.2dB and 5.11dB respectively[11].

Several researches have been conducted to study outdoor- to -indoor radio propagation characteristics with the intention of developing models that either capture the propagation characteristics in one go or combine separately analyzed outdoor, penetration and indoor losses to develop hybrid models.

Some of these research works used deterministic propagation models such as ray tracing model for predicting outdoor- to- indoor path loss and others had focused on empirical models for similar purpose. In [14] ray tracing techniques was used to study and characterize outdoor-to-indoor path loss of a roof top site located on building under study and operated on 800 and 1900MHz frequency bands. Detail structural information of the building was imported to simulation tool to establish simulation scenario and simulate in to the building propagation characteristics. The simulation result was compared with measurement data and the researchers were able to get reasonable result with considerable error margin; the error was mainly due to using over simplified building information.

In [12] a new outdoor-to- indoor propagation model had been suggested by considering path loss through openings such as doors and windows in contrast to propagation models such as COST231 which assumes the dominant path for radio signal propagation is through building walls. In this research work the outdoor-to-indoor propagation loss had been modeled by predicting the outdoor path, external wall penetration loss and path loss in the indoor environment separately and combining them. The newly proposed model was found out performing better than COST231 model.

In [19] empirical models such as free space, Keenan Motley and PLS models were compared and tuned using curve fitting and linear regression techniques for 385,900 and 1800MHz frequency bands. It was identified that PLS performed better than the other models in the specified environment. But this thesis work considered only single floor of a campus building in Stockholm.

To enable optimal planning of dedicated indoor solution, indoor models that assume both transmitter and receiver are located in the indoor environment or building are required. Several research works were conducted to model this indoor scenario. In one of these works [21] multi floor model by Keenan Motley had been taken as basis and correction factor was added based on analysis of measurement data taken. In this model on top of floor attenuation factor, attenuation due to partitions was considered. For the two building considered path loss exponent of 1.8 and 0.9 was reported. The lower path loss exponent, 0.9, in one of the buildings was observed due to wave guide effect of metal cases located along the building corridor.

Similarly a study was conducted in a train car for 800, 900, 1800, 2100 and 2600MHz frequency bands and one slope path loss model had been constructed. The reported path loss component at lower frequency is around 1.5 and for higher frequency bands it is around 2 [23].

## 1.4. Scope and limitation of the thesis

### 1.4.1. Scope of work

This thesis work includes determining BPL for representative sample buildings in Addis Ababa by undertaking measurement campaign to measure received signal strength at selected outdoor and indoor reference data points. Eight buildings are considered for measurement campaign and the measurement is taken up to sixth floor of the buildings. Received signal strength measurements will also be taken inside of the building at selected data points to determine and characterize signal path loss within a building. Based on the measurement taken two commonly used outdoor- to- indoor empirical radio propagation models, PLS and log-normal shadowing, will be compared and optimized.

In this thesis work frequency bands of 900MHz, 1800MHz and 2100MHZ are considered for BPL analysis and only 1800MHz is considered for outdoor- to- indoor propagation models comparison, analysis and model parameter tuning. Major focus will be given to open spaces, corridors and large rooms.

### 1.4.2. Limitation of the thesis

In this research work parameters such floor gain will not be investigated in detail. The penetration loss due to internal wall, partition and floor loss may not be treated separately.

## 1.5. Methodology

Sample representative buildings in dense urban and urban areas of Addis Ababa will be selected with some defined criteria. Relevant building information such as building material and thickness that will be used to investigate and determine BPL will be collected. The exterior walls of the building that are directly illuminated by the antenna of outdoor macro site will be selected, outdoor reference data points will be set at distance of 60cm to 1m from the walls at the ground floor and similarly indoor reference data points will be set at 60cm to 1m from the wall. Received signal strength measurements will be taken for 2 to 4minutes at each of the reference data points. Mean received signal strength at each data points will be considered to calculate the building penetration loss as difference between the outdoor and indoor mean signal strength of corresponding data points. All the BPL calculated for each corresponding pair of outdoor and indoor data points will be averaged to determine the BPL of the building.

Literature is reviewed to select two commonly used outdoor- to- indoor propagation models, comparison and tuning will be done based on measurement. Measurement inside the building will be taken mainly along the corridors, opens spaces and wider rooms. The measurements will be taken at every 2 to 5m depending on the length of the corridors and open spaces and relative path loss will be determined at every measurement point. Reference points will be set at the interior of the illuminated external walls, received signal strength measurements will be taken at these points and average of the measured signal strength will be considered as reference signal source to determine relative path loss at each data points. Linear regression and curve fitting techniques will be used to tune the propagation models. Finally the outdoor- to- indoor propagation path loss model will be determined as combination of outdoor propagation model, BPL and tuned indoor propagation model.

Live outdoor macro sites will be used as transmitter, smart phone installed Nemohandy drive test tool will be used as data collecting tool and Actix analyzer will be used to analyze the collected data.

## 1.6. Contribution of the thesis

Very high level survey conducted in 2015 in Addis Ababa indicated that up to 40% of the mobile traffic had been generated from indoor environment; at the time of this thesis has been conducted it is expected this ratio to be much higher than the above mentioned figure as building density has increased by many folds since then. The indoor cellular services have been provided by outdoor macro sites.

Both coverage and capacity planning of the outdoor cellular networks have been done mainly by considering the outdoor radio environments only; as a result the required coverage target, quality of service (QoS) and capacity in the indoor environment cannot be achieved. There has not been any considerable effort to alleviate this problem by studying local outdoor- to- indoor radio propagation characteristics and incorporating in radio planning practices.

This thesis work will determine BPL for the most common types of buildings in Addis Ababa. It also identifies and tunes two commonly used indoor propagation path loss models so they can be used in the indoor coverage planning. By doing so the research work will support to realize optimal cellular networks planning that address indoor coverage problem in the city of Addis Ababa. .

## 1.7. Thesis Organization

The thesis work will have six chapters. Chapter2 will give an overview of indoor coverage and solution importance, indoor solution types and indoor solution trends as motivational spring board for the thesis work. Chapter3 will give some background on propagation models focusing on outdoor -to- indoor and indoor propagation models.

In Chapter4 all measurement related activities will be discussed. Chapter 5 will address the analysis, results and discussion. Finally in Chapter6 conclusion of the thesis work will be provided and future works will be suggested.

# Chapter 2

## 2. Indoor coverage planning and solutions

Addis Ababa is expanding fast and turning into built up city; building density has drastically been increasing since the last few years. The building types have also been changing from simple to complex multistory buildings which serve as shopping malls, hotels, business offices and residential complexes. This changing feature of the city has significant impact on outdoor, outdoor-to-indoor and indoor radio propagation characteristics. The outdoor-to-indoor and indoor radio propagation characteristics further impacted by building material types and frequency. This new development calls for the need for treating indoor coverage and capacity planning more cautiously. The planning exercise should take into consideration radio signal propagation characteristics and customer behavior in such environment.

### 2.1. Why indoor coverage?

As more and more mobile users are staying indoor, mobile traffic that is generated in the indoor environment increases by day. As indicated in [25] in most cities few important buildings generate the major part of mobile traffic and in some cities 50% of the traffic is generated by 10% of the buildings.

A network operator can be motivated to insure indoor coverage by commercial opportunity that indoor traffic will bring and/or technical aspects that improve customer experience. Some of the technical drivers are: lack of coverage, more capacity, improving OoS, offloading outdoor macro sites and addressing high speed data rate need.

## 2.2. Indoor coverage approaches

As indicated in Figure2.1 mainly two approaches, outdoor sites and dedicated indoor solutions, are used to cover indoor environment. Both have their own advantage and disadvantage from planning and deployment complexity, cost, future expansion and maintenance perspective. It is required to investigate these aspects in detail before selecting one indoor solution over the other.

### 2.2.1. Indoor coverage by outdoor sites

Macro site extension and enhancements, outdoor sites densification and using lower frequency bands are the major approaches that can be considered during planning and optimization phases to address indoor coverage and capacity requirements from outdoor sites.

This approach is relatively inexpensive way of providing network coverage inside building. But it is insufficient and at time expensive to provide deep indoor coverage from outdoor macro sites in urban and dense urban environment where radio propagation relies on reflection, diffraction and scattering mechanisms. The impact of these propagation mechanisms is big on WCDMA based technologies such as HSPA+ as multipath effect decreases orthogonality efficiency of the radio channel and increase soft hand over (SHO) load due to lack of dominant channel which results in lower capacity [25].

### 2.2.2. Indoor coverage by dedicated indoor solution

In this approach, indoor solutions such as Distributed Antenna System (DAS), Repeaters, Small cells and Wi-FI are deployed in the indoor environment as dedicated network to provide the intended coverage and /or capacity targets.

Dedicated indoor solutions decrease the down link power per user that WCDMA/HSPA base station needs to allocate to serve the indoor environment by doing so it improves the capacity of the outdoor macro sites. But dedicated indoor solutions such as DAS are relatively expensive, cumbersome to deploy and maintain, and cannot be easily kept when the buildings will be reconstructed and expanded. Solutions such as repeaters provide only coverage enhancement, while Wi-Fi provides only data offloading for macro-cellular sites.

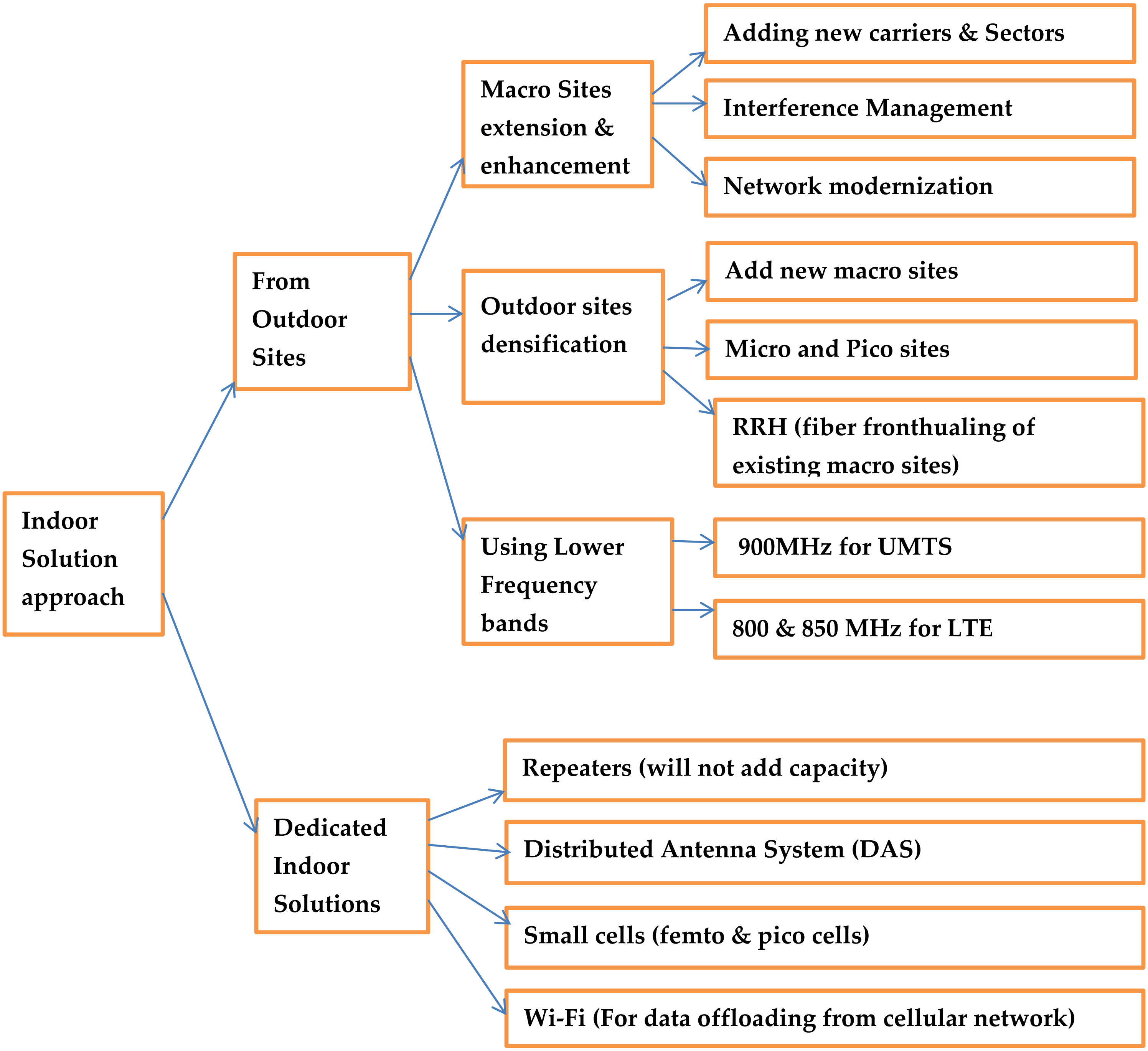


Figure 2.1. Indoor solution approaches.

## 2.3. Indoor environment in the era of 5G

According to [27] three major 5G services have been proposed, namely Enhanced Mobile Broadband (eMBB) , Ultra-Reliable and Low-Latency Communication (URLLC) and Massive Machine Type Communications (mMTC). These services require the network (whether it is outdoor or indoor) to support 100Mbps downlink cell edge rate, 1ms latency and 99.999% reliability. It is also expected to have 1 connections/m2 in the indoor environment.

As 5G is expected to use C-band and mmWave frequency bands propagation and penetration loss will be much higher and makes outdoor-to-indoor propagation scenario unviable option for indoor 5G coverage. Hence indoor solutions need to be deployed in such a way that they can deliver 5G targets and need to be future-proof.

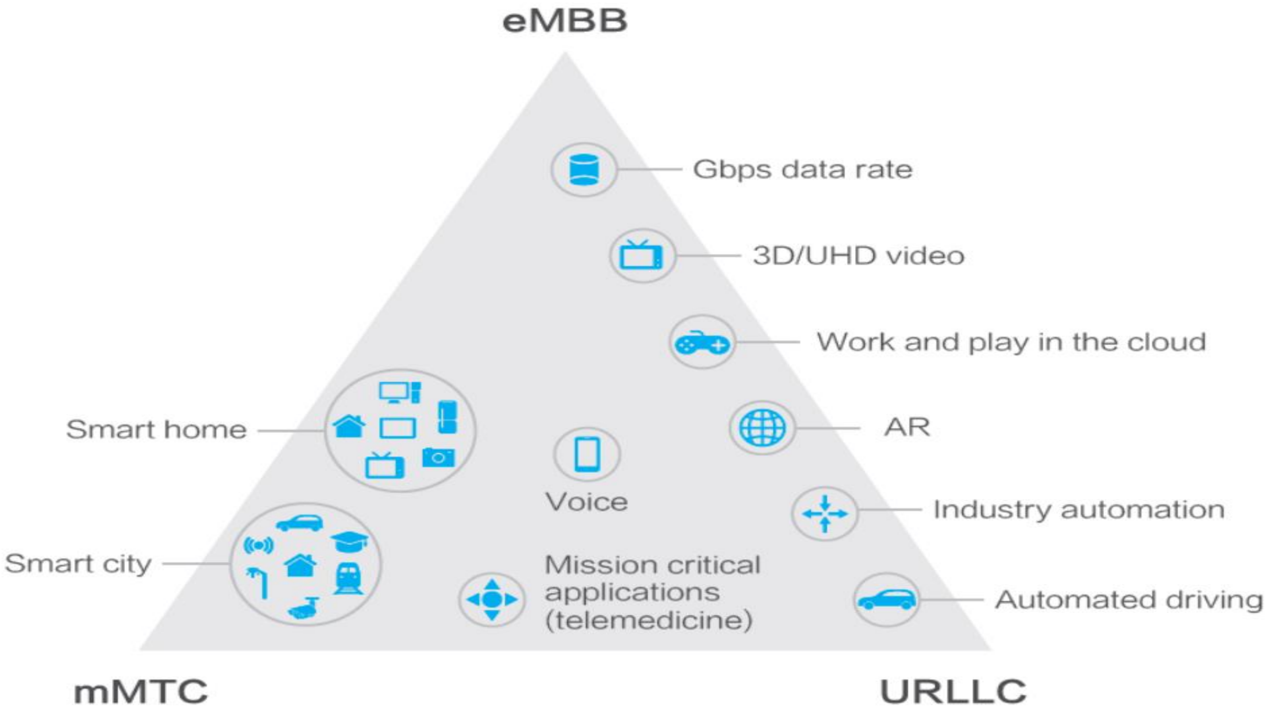


Figure 2.2. 5G services [27].

# Chapter 3

# 3. Radio propagation models

## 3.1. General

Radio propagation models are often used to characterize radio propagation in outdoor and indoor environments and are represented by mathematical expressions that are formulated in terms of distance, frequency, antenna height and other relevant parameters. Radio propagation happens in the air interface where radio wave travels between transmitters and receivers, ideally taking direct path in the space. But the propagation is always affected by natural and man- made obstacles which results in propagation path loss.

Propagation path loss is due to many effects such as free space loss, refraction, reflection, diffraction, scattering, and penetration losses. Path loss is also impacted by terrain contour, environment, transmitter to receiver distance and height and location of antenna.

In the indoor environment the propagation path loss can be contribution of all the following:

### A. Penetration into the building loss

This occurs when a signal is received from the external transmitter inside buildings and it is mainly due to external walls penetration loss of the buildings. Based on relative position of transmitter and receiver antenna and transmission environment condition (LOS condition) the signal strength may increase as the height of the building increases.

### B. Partition/Internal wall Loss.

This is a path loss due to penetration loss of internal walls and partitions as signal propagates in building. This loss is determined by factors such as building layout and structure, building material, partition and wall thickness and number of windows.

### C. Attenuation

Radio signal strength declines as it propagates in the indoor environment. Path loss is normally increases in logarithmic scale as propagation distance increases. Fading and multipath effect are also contribute to propagation path loss in the indoor environment**.**

## 3.2. Propagation model classification

Based on analysis techniques used propagation path loss models can be classified as empirical, deterministic and semi-deterministic as depicted in Figure3.1.

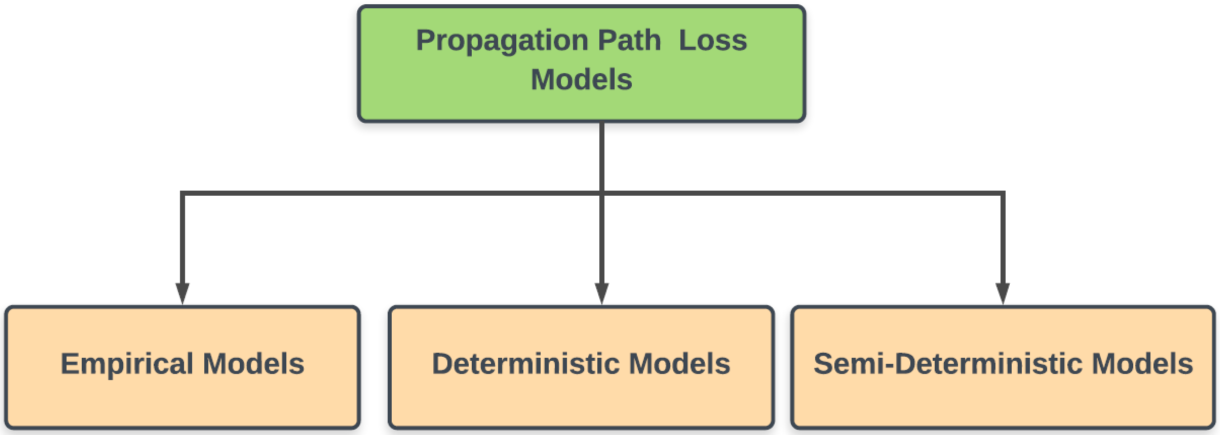


Figure 3.1. Propagation path loss classification based analysis technique used.

Propagation path loss models can also be classified based on relative position of transmitter and receiver. As indicated in Figure3.2 based on different transmitter and receiver positioning scenario propagation path loss models can be classified as outdoor, outdoor-to-indoor, indoor and indoor to outdoor models.

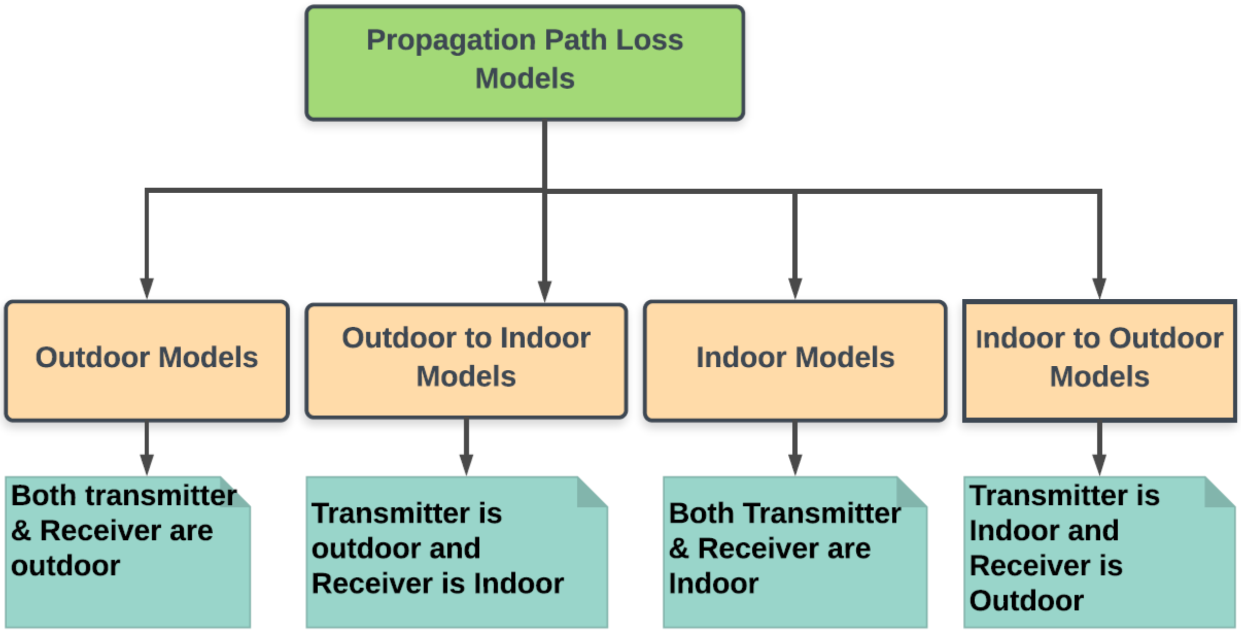


Figure 3.2. Propagation path loss classification based on transmitter and receiver relative positions.

### 3.2.1. Empirical propagation models

They are measurement data based propagation models that are built from extensive path loss field measurements using statistical analysis [24][28]. They exist for various outdoor and indoor environments and this thesis also focuses on the empirical types of propagation models. Empirical models usually express path loss as function of common parameters such distance, frequency and antenna height. While establishing the empirical models usually assumption are made and some simplifications are undertaken as a result they are simpler to compute and easier to implement. They are reasonably accurate for environments similar to those where the measurements were taken while the models are developed.

### 3.2.2. Deterministic and semi-deterministic propagation models

Deterministic propagation models are established based on detail simulation of radio propagation; the simulation takes in consideration radio propagation effects such as reflection, refraction, and diffraction. These models are considerably accurate but need detail geometric information about the building. Deterministic models are site specific and need considerable computation effort and resources.

Semi-deterministic models are combination of deterministic and other models such as empirical models. These models are usually used to improve the efficiency of purely deterministic models. In some specific scenario the main signal path is predicted by deterministic approach and the other signal paths will be handled by empirical models.

### 3.2.3. Indoor propagation models

In indoor environment transmitter to receiver distance is shorter compared to outdoor environments, and the radio channel varies with environment which makes indoor propagation modeling difficult.

Even if free space propagation model is not considered as indoor propagation model, it has been used in many indoor propagation models development to calculate path loss at close-in reference point which is part of these propagation models.

In this section the main empirical indoor propagation models which are one of the areas that have been covered by this thesis will be discussed.

### A. Free space propagation model

Free space radio propagation is a propagation scenario where there is no obstruction between transmitter and receiver. The free space propagation path loss model which is established based on Friis free space equation is given as [28],

$$\frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2 \qquad (3.1)$$

$$PL(d) = \frac{G_t G_r P_t}{P_r} = \left( \frac{4\pi d}{\lambda} \right)^2 = \left( \frac{4\pi df}{c} \right)^2 \qquad (3.2)$$

Where $P_r$ is the received power at transmitter to receiver distance d, $P_t$ is the transmitted power, $G_t$ and $G_r$ are transmitter and receiver antenna gains respectively, $\lambda$ is the wave length, $f$ is frequency of the radio wave and $c$ is speed of light.

The free space path loss, $PL(dB)$ , is expressed in logarithmic scale as:

$$PL(db) = 32.4 + 20\log(d) + 20\log(f) \qquad (3.3)$$

### B. Path loss slope (one slope ) model

PLS model is established based on the assumption that path loss in dB is linearly dependent on transmitter to receiver logarithmic distance $d$ [19][29]. This model depends on free space path loss determined at close-in reference distance $d_0$ and the path loss, $PL(db)$, is given as:

$$PL(d) = PL(d_0) + 10n\log(d) \qquad (3.4)$$

Where, $n$ is path loss exponent that indicates the rate at which radio signal decays in the given environment.

### C. Log-normal shadowing

Log-normal shadowing model is the modified version of path slope model that captures the effect of shadow fading due to different clutters in the propagation environment [29]**.** The shadow fading has log-normal distribution and the path loss is determined as:

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \quad (3.5)$$

Where, $X_\sigma$ is zero-mean normally (Gaussian) distributed random variable with standard deviation $\sigma$.

### D. Wall and floor factor models

Wall and floor factor models are determined by taking free space path loss and adding path loss due to walls and floors on top of it [28]. The path loss is linearly related to number of walls $n_w$ and number floors $n_f$.

$$PL(d) = L_1 + 20\log(d) + n_f L_f + n_w L_w \quad (3.6)$$

Where $L_1$ path loss is calculated at 1m transmitter to receiver reference distance, $L_f$ is penetration loss per floor and $L_w$ is penetration loss per wall.

### E. Cost231 multi-wall model

Cost231 multi-wall model is improved version of wall and floor factor models. It incorporates the non-linear component of the path loss through introducing complex term which depends on number of floors penetrated [28].

$$PL(d) = L_{FS} + L_C + \sum_{i=1}^{W} L_{wi} n_{wi} + L_f n_f^{\left(\left(\frac{n_f+2}{n_f+1}\right)-b\right)} \qquad (3.7)$$

Where $L_{FS}$ is free space path loss for direct path between transmitter and receiver, $L_C$ and $b$ are constants that are determined empirically, $L_{wi}$ is the penetration loss for a wall of type $i$, $n_{wi}$ is the number of walls of type $i$, $w$ is the number of wall types, $n_f$ is the number of floors, $L_f$ is the penetration loss per floor.

## 3.2.4. Outdoor-to-indoor propagation models

The motivation to study outdoor-to-indoor propagation models which characterize penetration and in building losses is to effectively serve the highly populated indoor environment. These propagation models are usually given as combination of outdoor path loss, path loss due to building penetration and path loss in the indoor environment [12][30]. This thesis also follows similar approach.

In this approach total propagation path loss, $L_p$ is determined as:

$$L_p = L_{out} + L_{pn} + L_{in} \qquad (3.8)$$

Where, $L_{out}$ is outdoor path loss component, $L_{pn}$ is building penetration loss and $L_{in}$ is propagation path loss in the indoor environment.

### A. Cost 231 line -of -site model

It is a model suggested when line of site exists between outdoor antenna building face as indicated in Figure3.3 [28]. Here $d_e$ is straight line path length between outdoor antenna and reference point on building wall and $\theta$ is incident angle which is given as $\theta = \cos^{-1}\left(\frac{d_p}{d_e}\right)$.

$$L_P = L_{FS} + L_e + L_g\left(1-\cos\theta\right)^2 + \max\left(L_1, L_2\right) \tag{3.9}$$

Where $L_{FS}$ is free space path loss for the total length (sum of outdoor and indoor path length), $L_e$ is path loss through the external wall at normal incidence ($\theta$=0), $L_g$ is additional path loss at external wall that occurs at grazing angle ($\theta$=90), and $L_1$ & $L_2$ are given as:

$$L_1 = n_w L_i\,,\; L_2 = \alpha\left(d_i - 2\right)\left(1-\cos\theta\right)^2 \tag{3.10}$$

Here $n_w$ is the number of walls crossed by indoor propagation path $d_i$, $L_i$ is path loss by internal walls and $\alpha$ is attenuation factor that applies to unobstructed internal wall.

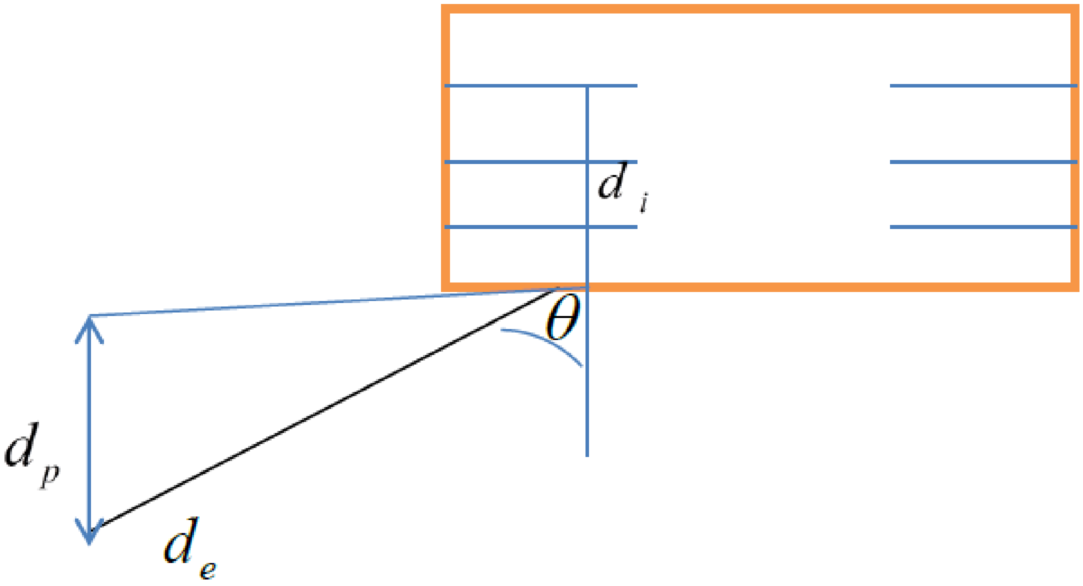


Figure 3.3. Cost 231 Line-of-Site propagation model geometry [28].

### B. Cost231 none-line-of-site model

This model relates path loss inside building from outdoor transmitter to external path loss measured at 2m above the ground and nearest side of the wall under study [28]. Cost231 none-line of site model is given as:

$$L_p = L_{out} + L_e + L_{ge} + \max(L_1, L_3) - G_{fh} \tag{3.11}$$

Where, $L_3 = \alpha d_i$ and $\alpha$ , $d_i$ $L_e$ and $L_1$ are as defined in Cost231 line of site model and $G_{fh}$ is floor height gain which is given as :

$$G_{fh} = \begin{cases} nG_n \\ hG_h \end{cases} \tag{3.12}$$

Where, $h$ is floor height from outdoor reference height and $n$ is number of floors.

There are several empirical out door to indoor propagation path loss models which are variants of the above discussed two fundamental models [12][30][31].

## 3.3. Propagation model tuning

A radio propagation model which is developed for one specific environment cannot be effectively used in another environment with different radio propagation characteristics. Hence for optimal radio planning, it is necessary to adjust propagation model parameters based on measurement data taken in the new environment. This process of radio propagation models adjustment is referred to as model tuning.

Curve fitting is one the techniques that is usually used for model parameter tuning by identifying mathematical expression that best fit measurement data [33]. Regression analysis is used to estimate the model parameters by trying to minimize residual errors between the fitted model and measurement data. In this thesis work both curve fitting and linear regression technique are used. Specifically least square method which tries to minimize residual error sum of squares that often called the sum of squares of the errors about the regression line and is denoted by SSE has been used. Residual error to be minimized is given as [33]:

$$e_i = y_i - \hat{y}_i, \quad i = 1, 2, \ldots, n. \tag{3.13}$$

Where, $y_i$ is measurement data and $\hat{y}_i$ is fitted model which is given as:

$$\hat{y}_i = b_0 + b_1 x_i \tag{3.14}$$

Here $b_0$ and $b_1$ are model parameters to be estimated.

Step by step procedure to estimate the model parameters is as follows:

$$SSE = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 = \sum_{i=1}^{n} \left(y_i - b_0 - b_1 x_i\right)^2 \tag{3.15}$$

Differentiating Equation 3.15 with respect to $b_0$ and $b_1$, setting the partial derivative equal to zero and solving for $b_1$ and $b_0$ gives,

$$b_1 = \frac{n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{n\sum_{i=1}^{n} x_i^{2} - \left(\sum_{i=1}^{n} x_i\right)^{2}} \qquad (3.16)$$

$$b_0 = \frac{\sum_{i=1}^{n} y_i - b_1 \sum_{i=1}^{n} x_i}{n} \qquad (3.17)$$

As $b_0$ and $b_1$ are intercept and slope of linear equation respectively, Equation 3.16 and 3.17 can be used for parameter estimation of linear propagation models.

## Chapter 4

# 4. Measurement Set up

One of the main tasks of this thesis work has been field measurement. Field measurement in general and indoor field measurement in particular is a very challenging task as it needs a lot of logistical coordination and resources. In this chapter all the measurement preparation, set up and campaign will be discussed.

## 4.1. Building selection

Before starting the measurement campaign representative sample buildings have been selected based on predefined criteria. Accordingly eight buildings have been selected and measurement has been conducted at eight of them. The criteria that are used for building selection are:

### A. Morphology and purpose of the building

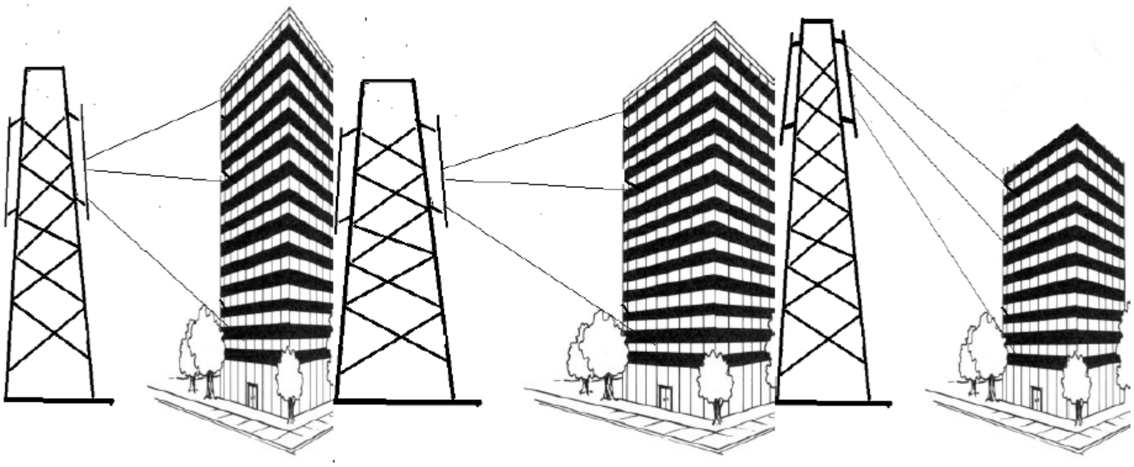
It has been intended to select representative buildings from dense urban, urban and suburban areas of the city that are used as office, shopping malls, residential apartments and hotels.

### B. Building material

Those building that are made from most commonly used building materials such as hollow concrete blocks, bricks, glasses and stone blocks are selected.

### C. Building and antenna height

Relative height of building and outdoor site antenna has been considered. As indicated in Figure4.1 scenarios when height of a building and site antenna are approximately equal (to last floor of the building) and one higher than the other has been considered. Transmission condition in which outdoor site antenna directly illuminates the external wall of the building under study is taken to easily lock the transmitted channel selected for test and focus on direct path signal propagation.



Comparable height Building higher Antenna higher

Figure 4.1. Building and site antenna relative height.

### D. Indoor environment

Building with diversified internal layout has been selected. Some of the selected buildings have wide and long corridors with open areas and partitions that are made from aluminum and glasses and others have relatively narrow and short corridors as indicated in Figure4.2.

Figure 4.2. Internal building layout.

Four of the selected buildings are located in dense urban area of the city while the remaining four are located in urban area of the city. Most of the surveyed buildings in the suburban area of the city do not fit the measurement set up in this thesis work as result sub urban areas are excluded. Detail information of the selected building is provided in Table 4.1.

| **Buildings** | **Building Description** | **Building Material** | **Site Distance** |
|---|---|---|---|
| Building1 | ✓ Has relatively narrow & free corridors (less than 2m wide)<br>✓ Six floor building<br>✓ Office building | Hollow concrete blocks | Around 70m |
| Building2 | ✓ Has relatively narrow and open corridors (greater than 2m wide)<br>✓ Two floor building<br>✓ Office & training center | Mainly glass (painted) | Around 150m |
| Building3 | ✓ Has relatively wide and open corridors (greater than 4m wide)<br>✓ Four floor building<br>✓ Shopping mall | Mainly glass | Around 500m |
| Building4 | ✓ Has relatively narrow & free corridor (less than 2m wide)<br>✓ Measurement done up to 5th floor<br>✓ Student Dormitory | Mainly bricks | <50m |
| Building5 | ✓ Has relatively wide and long corridor (more than 4m wide and 105m long)<br>✓ Three floor building<br>✓ Education centers and office | Stone masonry & wide glass windows on the side | >500m |
| Building6 | ✓ Has relatively narrow corridors with some clutters<br>✓ Two floor building | Stone Masonry and narrow glass window | <50m |
| Building7 | ✓ Eight floor building | Majorly glass | <50m |
| Building8 | ✓ Very wide corridors and open spaces<br>✓ Has not been suitable to complete the measurement | Mainly glass | |

Table 4.1. Building detail information.

## 4.2. Propagation model selection

Based on literature review, three commonly studied outdoor -to –indoor and indoor propagation path loss models namely PLS, log-normal shadowing and Cost231 multi-wall models have been selected for the purpose of this thesis work. Cost231 multi-wall path loss model has component of penetration loss due to internal and external walls and floors. But floor penetration loss cannot be measured using outdoor transmitter; dedicated indoor transmitter is needed to conduct such measurement. As such measurement set up could not be arranged, Cost231 multi-wall model has been dropped.

The data deemed necessary to tune the remaining two models, PLS and log- normal shadowing, has been collected for the path loss model tuning purpose.

## 4.3. Data collection and tools

Before starting data collection and field measurement activities; the data to be collected, parameters to be measured, data collection and analysis tools to be used need to be identified. Measurement set up has to be properly designed and the measurement campaign needs to be well planned.

### 4.3.1. Data to be collected

In addition to building and site related information mentioned in Table 4.1, the data that indicates received signal level and signal quality is collected. Signal parameters such as Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Received Signal Code Power (RSCP), Ec/No, and Received signal strength indicator are collected.

RSRP, RSCP and Received signal strength indicator are used to determine outdoor-to-indoor path loss. The measured parameters are reported by the analysis tool as indicated in Figure4.3 for one particular data point at a given floor.

**900MHz (GSM)**

| Statistic | ServBCCH | Statistic | ServRxLevIdle |
|---|---|---|---|
| Mean | 114 | Mean | -74.26027397 |
| Mode | 114 | Mode | -74 |
| Median | 114 | Median | -74 |
| Maximum | 114 | Maximum | -71 |
| Minimum | 114 | Minimum | -81 |
| Count | 89 | Count | 73 |
| Standard Deviation | 0 | Standard Deviation | 2.643303233 |
| Variance | 0 | Variance | 6.98705198 |

1800MHz (LTE)

| Statistic | LTE_UE_PCI | Statistic | LTE_UE_RSRP | Statistic | LTE_UE_RSRQ |
|---|---|---|---|---|---|
| Mean | 130 | Mean | -91.05324703 | Mean | -7.380519471 |
| Mode | 130 | Mode | -90.90000153 | Mode | -7.400000095 |
| Median | 130 | Median | -90.90000153 | Median | -7.099999905 |
| Maximum | 130 | Maximum | -85.40000153 | Maximum | -6.400000095 |
| Minimum | 130 | Minimum | -101.6999969 | Minimum | -9.699999809 |
| Count | 77 | Count | 77 | Count | 77 |
| Standard Deviation | 0 | Standard Deviation | 3.86175291 | Standard Deviatio | 0.810649725 |
| Variance | 0 | Variance | 14.91313554 | Variance | 0.657152977 |

**2100MHz (WCDMA/HSPA+)**

| Statistic | Uu_ActiveSet_EcNo_0 | Statistic | Uu_ActiveSet_SC_0 | Statistic | Uu_ActiveSet_RSCP_0 |
|---|---|---|---|---|---|
| Mean | -10.79313724 | Mean | 156 | Mean | -82.31764737 |
| Mode | -13.30000019 | Mode | 156 | Mode | -80 |
| Median | -10.10000038 | Median | 156 | Median | -81 |
| Maximum | -4.900000095 | Maximum | 156 | Maximum | -73 |
| Minimum | -22.79999924 | Minimum | 156 | Minimum | -95.40000153 |
| Count | 102 | Count | 102 | Count | 102 |
| Standard Deviation | 3.880879687 | Standard Deviation | 0 | Standard Deviatio | 5.003497185 |
| Variance | 15.06122715 | Variance | 0 | Variance | 25.03498408 |

Figure 4.3. Measured signal parameters at one data point.

### 4.3.2. Data collection and analysis tools

Nemo handy version 2.71.391 which is handheld walk test tool suitable for in building measurements and supported on Android based terminals is used as data collection tool.

The Nemo handy is installed on Samsung galaxy S5, G900F and Samsung/SM-G900F that runs Android operating system version 4.4.2. The collected log file is exported to the analysis tool for necessary data conversion, analysis and presentation. This tool is selected as it has features that conveniently collect the required data and readily available in ethio telecom. The analysis tool used in this research work is a laptop, Dell/Latitude/E5430 that runs Windows10 operating system, installed Actix Analyzer version 5.5.328.879.

## 4.4. Measurement campaign

After selecting buildings, propagation path loss models and data collection and analysis tools, the measurement campaign is planned and commenced. The measurement campaign plan includes measurement approach and set up design for both outdoor and indoor measurements.

### 4.1.1. Measurement campaign plan and set up

Preparation for measurement campaign is started by acquiring the identified data collection and analysis tools; manpower that participates in the walk test and other resources such as vehicles. The necessary arrangements and facilitations are made to get the required level of access to measurements areas of each building

The total measurement campaign duration is set as six weeks assuming that 1.5 buildings (a building and some floors) can be covered weekly. Measurements are taken in working hours of week days and Saturdays. Measurements are taken up to sixth floor of a building whenever applicable.

In the measurement set up ethio telecom live commercial outdoor macro sites are used as transmitter for all the frequency bands, 900MHz, 1800MHz & 2100MHz, and Nemo handy installed Samsung terminals are used as radio receivers. Dominant radio channels of the three frequency bands with better signal strength are searched and locked; for specific site or building all measurements are taken on these channels. All the measurements are taken in idle mode. Measurement for the three frequency bands is taken at every data point.

### 4.1.2. BPL measurement approach and set up

BPL in this research work is taken as the difference in mean received signal strength between the signal level measurements obtained inside and a reference signal level measured near unobstructed outside wall of the building.

Outdoor reference data points are set adjacent to the ground floor, at 1m from exterior wall of the building that directly illuminated by transmitter antenna. Up to 10 data points are selected and received signal strength measurement is taken for about 2 minutes at each data point for each frequency bands. The measurement is taken at about 1.6 m high from ground or floor.

The mean of measured received signal strength samples at each reference data point is taken as outdoor reference signal for that particular data point. As indicated in Figure4.4 similar reference data points are set at inside of the wall corresponding to each outdoor reference data points. Similar to outdoor, measurements are taken at these interior reference data points and the mean received signal strength is taken as indoor reference signal for that particular indoor data point. The indoor measurement is done at all selected floors. The difference between outdoor reference signal strength and corresponding indoor reference signal strength at each floor is computed; the result is averaged to determine the building penetration of a floor and entire building.

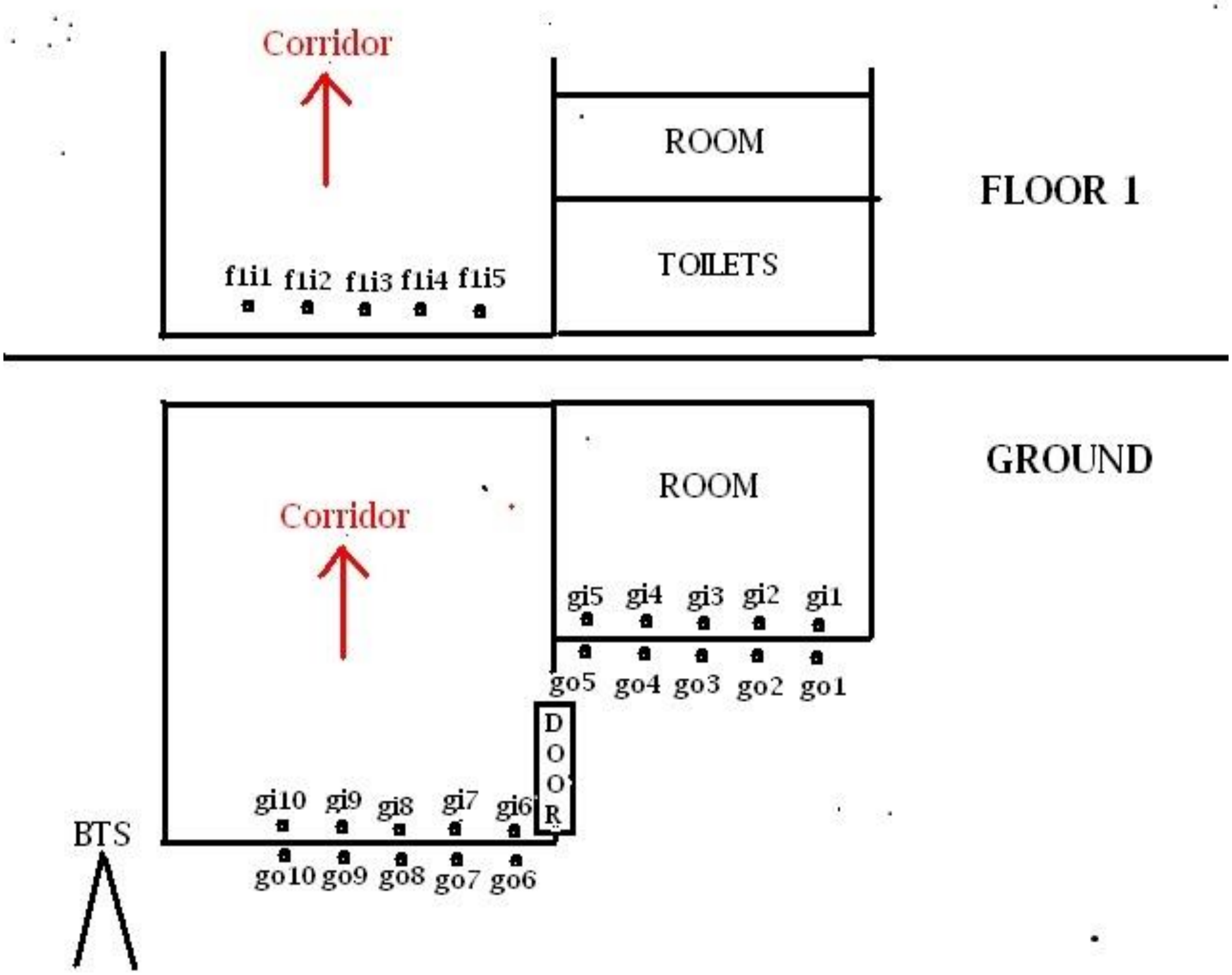


Figure 4.4. Reference signal measurement set up to determine BPL.

### 4.1.3. Indoor path loss measurement

Path loss (in dB) is computed as the difference between transmitted signal and received signal [24]. Propagation path loss of transmitted signal from outdoor macro site to in building receiver is comprised of path loss in outdoor environment, building external wall penetration loss and indoor environment path loss. The outdoor sites are at relatively far distance from nearest building entry points, as a result the outdoor component of the path loss is affected by different outdoor environmental factors. This kind of transmitter-receiver set up may not be convenient to characterize radio signal propagation in the indoor environment which rapidly changes in relatively shorter distance. For this kind of scenario the usual practice is putting both transmitter and receiver in building or putting transmitter at unobstructed location near to the external face of the wall [12][15] [19][21][30].

Hence, in this thesis to emulate in building transmitter average reference signals at the immediate interior of external wall that faces outdoor macro sites are measured at each floor. The average of these reference signals is determined and relative path loss is computed against the average reference signal as receiver is moved away from these points further into the building. Indoor reference signals are measured as indicated in Figure4.4 (data points: gi1, gi2…gi10) and Figure4.5 (data points: fi1 fi2—fi5).

As Global Positioning System (GPS) signal is not available at most part of indoor environment, it is not possible to capture location information by the walk test tool, as a result stationary test are conducted at data points set at defined interval from the reference point. The measurement is conducted at 2.4m and 5m interval depending on the length of corridors, open spaces and rooms. At each data point measurement is continuously taken for 2 minutes for 900MHz, 1800MHz and 2100MHz frequency bands. The mean of the collected data over the 2 minutes is taken as received signal strength at that specific data point and path loss at that data point is computed as the difference between the average reference signal and the mean received signal strength at that data point. The path loss at similar data points of each floor is aggregated and averaged to determine path loss characteristics against distance for the entire building.

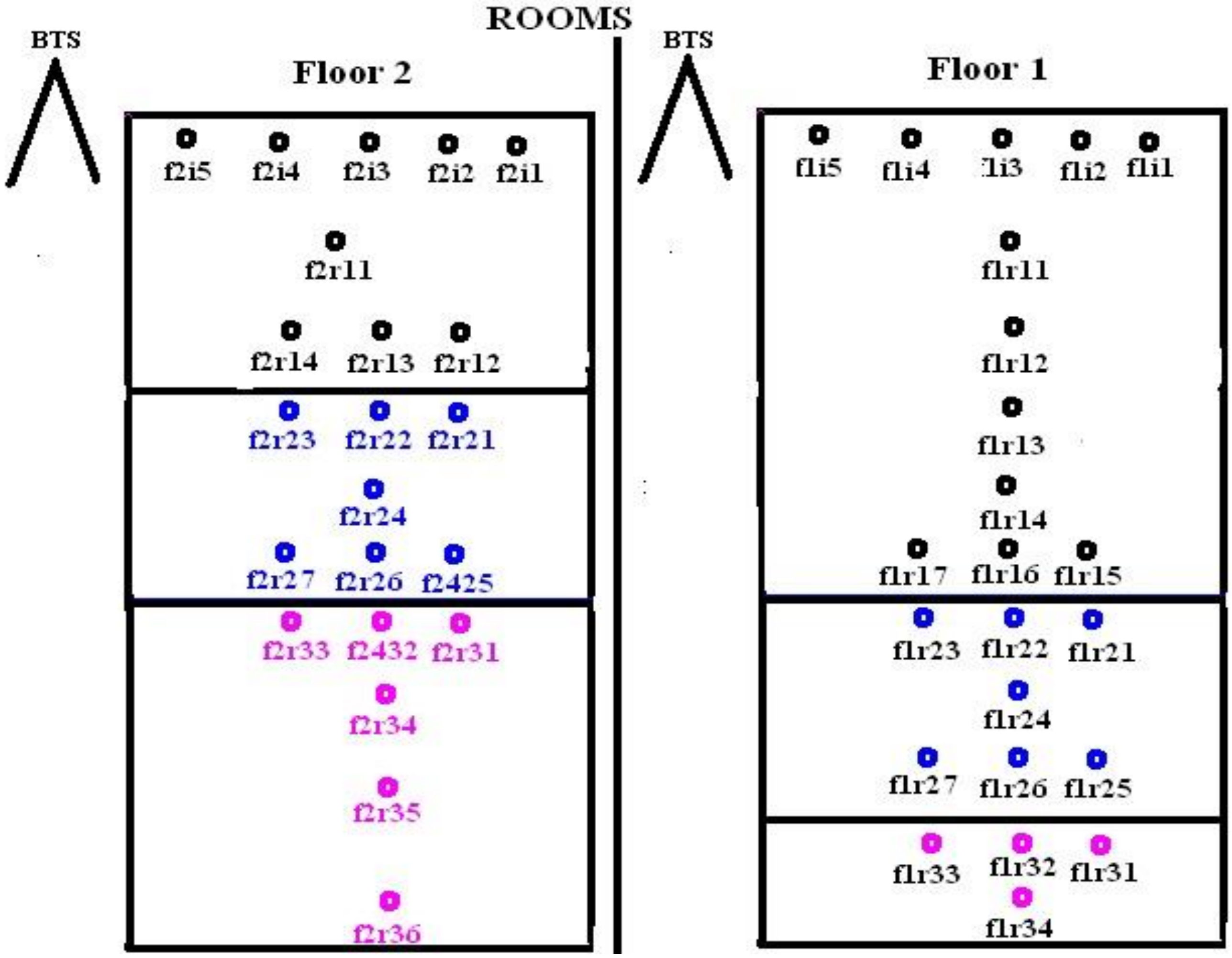


Figure 4.5. Indoor measurement set up.

# Chapter 5

## 5. Result and discussion

In this chapter the measured building, specifically external wall of building, penetration loss of radio signal with relevant analysis is presented and discussed. Tuned model parameters for the selected radio path loss propagation models are discussed and tuned outdoor-to-indoor models are suggested.

### 5.1. System set up and parameters

System set up is based on the fact that outdoor-to-indoor radio propagation path loss is consists of outdoor path loss, BPL and path loss in indoor environment components which are labeled as Lo , Lp & Li in Figure 5.1 and $L_{out}$, $L_{pn}$, and $L_{in}$ in Equation 3.8. The outdoor propagation path loss component is characterized and determined by outdoor propagation models which are not part of this research work. The BPL and propagation path loss in the indoor environment parts is closely investigated.

Average BPL which is determined based on measurement set up discussed in Chapter 4 is presented next.

The selected indoor propagation models, Equation 3.4 and 3.5 that of PLS and log-normal, are tuned based on measurement data from the measurement campaign to characterize the indoor path loss component of the outdoor-to-indoor radio propagation path loss. The tuned model parameters determined from measurement data using linear regression (least square method) are path loss at reference points ( $PL(d_0)$ ) and path loss exponent ( $n$ ). The path loss exponent ( $n$ ) indicates how fast the radio signal decays against distance in a given indoor environment scenario. Standard deviation ( $\sigma$ ) is also determined from measurement to capture the shadowing effect.

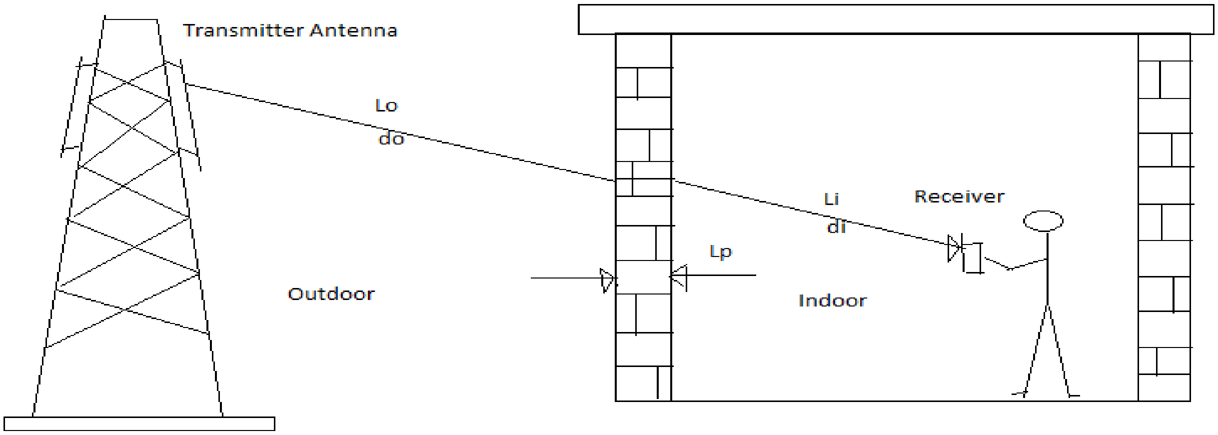


Figure 5.1. Outdoor-to-indoor propagation models system set up.

## 5.2. BPL analysis and determination

Measurement to determine building radio signal penetration loss is conducted at eight sample building for 900MHz, 1800MHz and 2100MHz. The analysis and results are presented for six of the buildings covering all three frequency bands and for one building covering 900MHz and 1800MHz.

Based on the material they are made from the building can be categorized in to three groups: those buildings dominantly made from glass, those made from hollow concrete blocks and bricks and those majorly made from stone masonry. The glasses are commonly 6mm thick and the hollow concrete block external walls are 25cm to 27cm thick. Most of the floors of these buildings are reinforced concrete slab which is 20cm to 22cm thick.

The average BPL and standard deviation (SD) for each building based on the measurements that has been taken at the ground floor is summarized Table5.1. For buildings that are made from hollow concrete blocks and bricks the BPL varies from 12.01dB to 17.7 dB and the result varies from building to building and depends on frequency bands. Similarly the variation for buildings made from stone masonry ranges from 14.16dB to 25.41dB. These figures are consistent with what is reported in literatures [10][24]. For those buildings made from glass the building penetration loss disparity among different buildings and frequency bands is considerably big, it ranges from 0.89dB to 10.36dB. The penetration loss for Building2 is significantly bigger than penetration loss of the other two glass buildings, Building3&Building7, this is possibly due to the glass is layered with sun protection material.

In general if penetration loss of specific material is measured in isolation, the penetration loss increases with frequency. But in practical building it is difficult to establish this trend, as a result it was reported in some studies that penetration loss increases with frequency and in others it decreases [28]. In this research it can be seen from the summarized result that penetration loss depends on frequency, though it is not possible to conclude it either increase or decreases with frequency. It can clearly be seen, it also depends on the building material types.

It is not possible to conclude that the building penetration loss reported in this thesis work completely comes from the building material penetration loss but effort is made to decrease the contribution from other factors by taking the outdoor and indoor reference measurement points closer to the wall.

| Buildings | Building Description | Frequency Band (MHz) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 900 | | 1800 | | 2100 | |
| | | BPL (dB) | SD | BPL (dB) | SD | BPL(dB) | SD |
| Building1 | Six Floor (Hollow concrete blocks) | 17.7 | 4.09 | 17.51 | 1.09 | 13.36 | 2.96 |
| Building2 | Three floor (majorly glass) & some part of hollow concrete blocks | 8.81 | 7.93 | 8.14 | 5.65 | 10.36 | 5.03 |
| Building3 | Four floor large mall (glass) | 2.56 | 2.27 | 0.89 | 0.96 | 6.25 | 9.56 |
| Building4 | Five floor (Brick) | 12.01 | 3.58 | 13.7 | 4.93 | 12.22 | 4.26 |
| Building5 | Three floor (Stone masonry) | 15.11 | 6.24 | 25.41 | 6.04 | 14.16 | 2.76 |
| Building6 | Two floor (Stone masonry) | 17.81 | 9.04 | 16.38 | 3.18 | 19.66 | 4.66 |
| Building7 | Eight floor (majorly glass) & some part of hollow concrete blocks | 2.46 | 1.1 | 1.62 | 1.87 | | |

Table 5.1. Summary of BPL.

## 5.3. Proposed model based on BPL

Even though outdoor macro and micro sites have a lot of limitations to serve the indoor environment, they are still viable options to address indoor coverage and capacity requirements. The usual network dimensioning practice to address indoor planning targets is to add building penetration loss margins to outdoor dimensioning inputs. This can be given by general model indicated by Equation 5.1.

$$PL = Outdoor\ model + BPL \tag{5.1}$$

That is the path loss indoor user experiences ( $PL$ ) is comprised of propagation path loss at outdoor environment which is predicted by outdoor propagation models and building penetration loss. The outdoor propagation models can be either the currently in use propagation models or propagation models that will be selected in the future.

But building penetration loss margins can be selected based on building category and frequency band as identified in this thesis.

This model can be useful for less conservative network dimensioning approach that intends to serve less populated small and medium buildings that do not have high indoor coverage target.

## 5.4. Indoor models tuning and analysis

Model parameters of the two selected indoor propagation path loss models, PLS and log-normal shadowing, are tuned based on measurement data collected. Simple linear regression and curve fitting techniques are used to determine tuned model parameters and the parameters are computed based on Equation 3.16 and 3.17. The main parameters to be determined are propagation path loss at reference distance and path loss exponent which are intercept and slope of the linear equations that represent the models respectively.

The propagation path loss model tuning is done building by building basis by selecting five buildings out of the eight buildings and the results are presented accordingly. The average of measured data of similar data points at every floor is considered to characterize indoor environment radio propagation path loss against distance. The model tuning is done per the measurement taken on 1800MHz frequency band as it is one of the frequency spectrum that are heavily used to deploy wide variety of mobile networks including GSM & LTE, and closer to 2100MHz frequency band which is widely used to deploy WCDMA based third generation (3G) mobile networks.

The accuracy of the model parameter tuning is measured by Root Mean Square Error (RMSE) that measures the difference between the measured path loss and the path loss predicted by the model.

### 5.4.1. PLS propagation model

Model parameters of PLS model which are given by Equation 3.4 are tuned for specific environment of each building and the result is provided building by building.

#### A. Building1

As discussed in the preceding chapters, internal environment of this building consists of corridors that are up to 2m wide and 29m long and open spaces. The measurements taken in this environment is provided in Table 5.2. At every floor of the building measurement is taken at eleven data points; and totally the measurement is taken at sixty six data points.

| Data Points | Distance from the reference point (m) | Log(di) | Average Path loss (dB) |
|---|---|---|---|
| 1 | 2.4 | 0.38 | 9.21 |
| 2 | 4.8 | 0.68 | 12.11 |
| 3 | 7.2 | 0.86 | 13.69 |
| 4 | 9.6 | 0.98 | 13.97 |
| 5 | 12 | 1.08 | 13.65 |
| 6 | 14.4 | 1.16 | 14.22 |
| 7 | 16.8 | 1.23 | 14.87 |
| 8 | 19.2 | 1.28 | 16.83 |
| 9 | 21.6 | 1.33 | 16.55 |
| 10 | 24 | 1.38 | 19.10 |
| 11 | 26.4 | 1.42 | 19.73 |

Table 5.2. Measured average path loss (Building1).

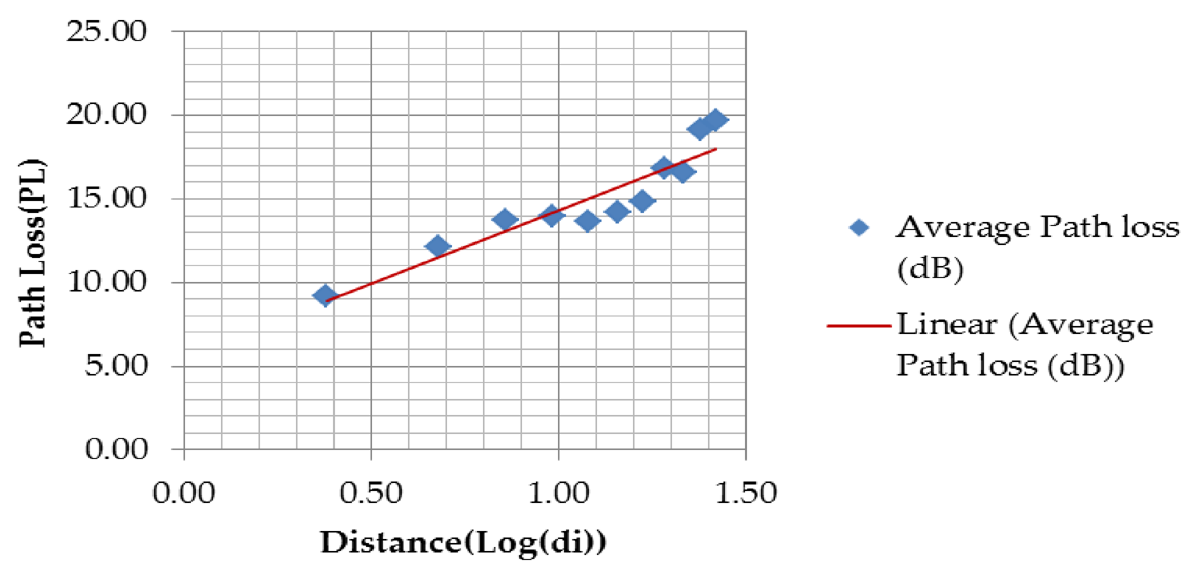


Figure 5.2. Curve fitted measurement data (Building1).

To determine the desired propagation model for the building $b_0$ and $b_1$ are computed as 5.57 and 8.71 respectively. Hence, the tuned propagation model is given as:

$$PL(d) = 5.57 + 8.71\log(d) \tag{5.2}$$

The path loss exponent $n$ is computed as 0.871 and this figure is much less than 2 which is path loss exponent of free space. This may be due to less clutter density and wave guiding effect of the relatively narrow corridors. But the result is close to the value reported in some literatures [21]. The RMSE value is determined as 1.064dB which indicates the tuned model is fairly accurate.

### B. Building3

Building3 is large shopping mall with a lot of open spaces and wide and long corridors. The corridors are more than 4m wide and 45m long. The measurement is taken at sixty eight data points on all floors of the building. The measurement result is provided in Table 5.3. The model parameters $b_0$ and $b_1$ are computed as -2.71 and 16.36 respectively. The tuned propagation model is given as:

$$PL(d) = -2.71 + 16.36\log(d) \tag{5.3}$$

The intercept of the equation is negative this is due to received signal strength at some data points is more than the signal strength at reference points. The path loss exponent is determined as 1.64 and it is close to figures reported in literature [21][24]. The RMSE value, 2.036dB, is considerably greater than the value reported for Building1 but it still indicates good level of accuracy of the tuned model.

| Data Points | Distance from the reference point (m) | Log(di) | Average Path loss (dB) |
|---|---|---|---|
| 1 | 2.4 | 0.38 | 8.43 |
| 2 | 4.8 | 0.68 | 8.81 |
| 3 | 7.2 | 0.86 | 7.21 |
| 4 | 9.6 | 0.98 | 11.35 |
| 5 | 12 | 1.08 | 13.05 |
| 6 | 14.4 | 1.16 | 15.63 |
| 7 | 16.8 | 1.23 | 17.26 |
| 8 | 19.2 | 1.28 | 17.82 |
| 9 | 21.6 | 1.33 | 17.80 |
| 10 | 24 | 1.38 | 19.04 |
| 11 | 26.4 | 1.42 | 19.39 |
| 12 | 28.8 | 1.46 | 20.11 |
| 13 | 31.2 | 1.49 | 22.33 |
| 14 | 33.6 | 1.53 | 23.40 |
| 15 | 36 | 1.56 | 25.37 |
| 16 | 38.4 | 1.58 | 24.82 |
| 17 | 40.8 | 1.61 | 25.88 |

Table 5.3. Measured average path loss for Building3.

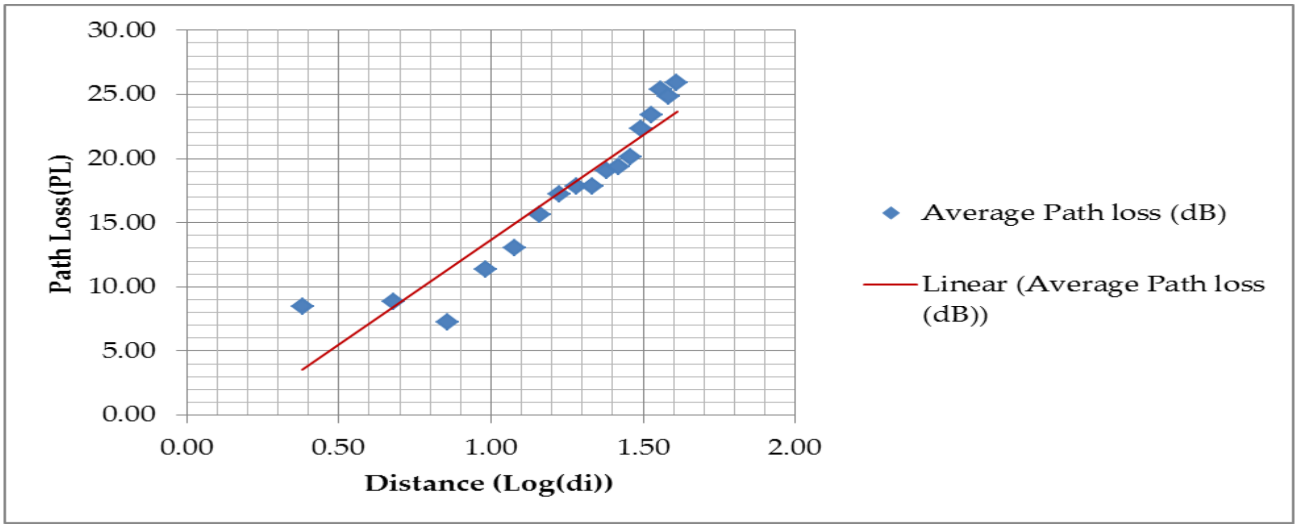


Figure 5.3. Curve fitted measurement data (Building3).

### C. Building4

This building is similar to Building1 with relatively narrow corridors but the corridors and open spaces are free of obstructions. The average path loss is measured at sixty data points on all floors of the building.

The values of model parameters are computed as 4.92 and 5.15 from measurement data provided in table5.4 and the tuned propagation model is determined accordingly.

$$PL(d) = 4.92 + 5.15\log(d) \tag{5.4}$$

The path loss exponent is identified as 0.52 which is lower than the path loss exponents of other buildings that are reported in this thesis work; this is mainly due to wave guiding effect of the narrow and clutter free corridors.

The RMSE which is computed as 3.13dB is relatively greater than RMSE values of Building1, Building3 and Building6 but it is comparable or better than the value that was reported in some literatures [23].

| Data Points | Distance from the reference point (m) | Log(di) | Average Path loss (dB) |
|---|---|---|---|
| 1 | 5 | 0.70 | 3.84 |
| 2 | 10 | 1.00 | 10.83 |
| 3 | 15 | 1.18 | 15.81 |
| 4 | 20 | 1.30 | 13.29 |
| 5 | 25 | 1.40 | 12.73 |
| 6 | 30 | 1.48 | 16.00 |
| 7 | 35 | 1.54 | 15.33 |
| 8 | 40 | 1.60 | 11.28 |
| 9 | 45 | 1.65 | 9.07 |
| 10 | 50 | 1.70 | 10.79 |

Table 5.4. Measured average path loss for Building4.

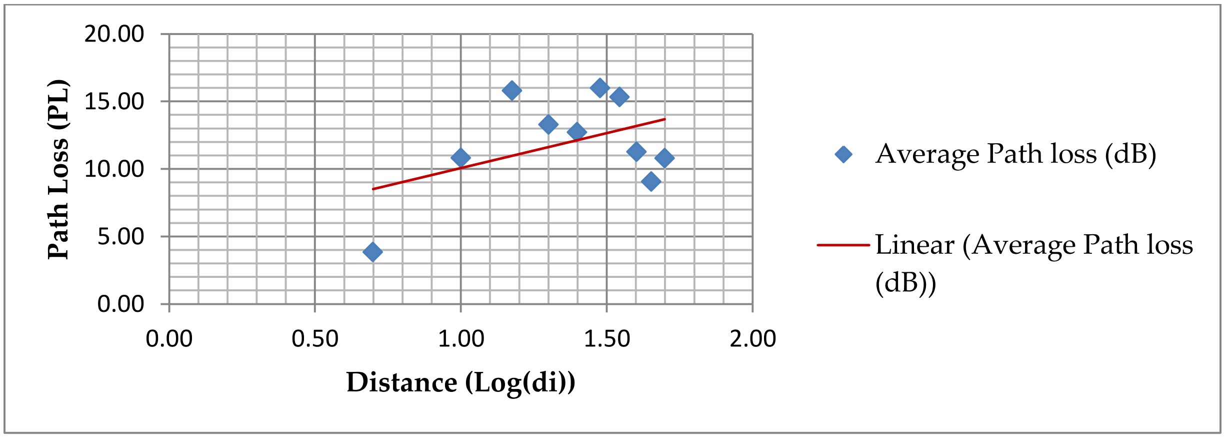


Figure 5.4. Curve fitted measurement data (Building4).

### D. Building5

This building is similar to Building3 in some aspects but the corridors are much longer. Measurements are done at eighty three data points at all floors of the building and the measured average path loss is indicated in Table5.5. The model parameters, $b_0$ and $b_1$ are computed as -11.85 and 18.06 respectively. Accordingly the tuned model for this building is given as:

$$PL(d) = -11.85 + 18.06\log(d) \tag{5.5}$$

The path loss exponent and RMSE are determined as 1.81 and 5.53dB respectively. Similar to that of Building3, the path loss exponent identified here is closer to what was reported in the literatures.

| Data Points | Distance from the reference point (m) | Log(di) | Average Path loss (dB) |
|---|---|---|---|
| 1 | 5 | 0.70 | 9.29 |
| 2 | 10 | 1.00 | 9.57 |
| 3 | 15 | 1.18 | 10.85 |
| 4 | 20 | 1.30 | 12.50 |
| 5 | 25 | 1.40 | 11.80 |
| 6 | 30 | 1.48 | 7.87 |
| 7 | 35 | 1.54 | 9.48 |
| 8 | 40 | 1.60 | 13.37 |
| 9 | 45 | 1.65 | 11.00 |
| 10 | 50 | 1.70 | 10.02 |
| 11 | 55 | 1.74 | 16.64 |
| 12 | 60 | 1.78 | 18.44 |
| 13 | 65 | 1.81 | 17.24 |
| 14 | 70 | 1.85 | 17.63 |
| 15 | 75 | 1.88 | 17.36 |
| 16 | 80 | 1.90 | 25.82 |
| 17 | 85 | 1.93 | 26.86 |
| 18 | 90 | 1.95 | 30.20 |
| 19 | 95 | 1.98 | 33.32 |
| 20 | 100 | 2.00 | 30.81 |
| 21 | 105 | 2.02 | 32.15 |

Table 5.5. Measured average path loss for Building5.

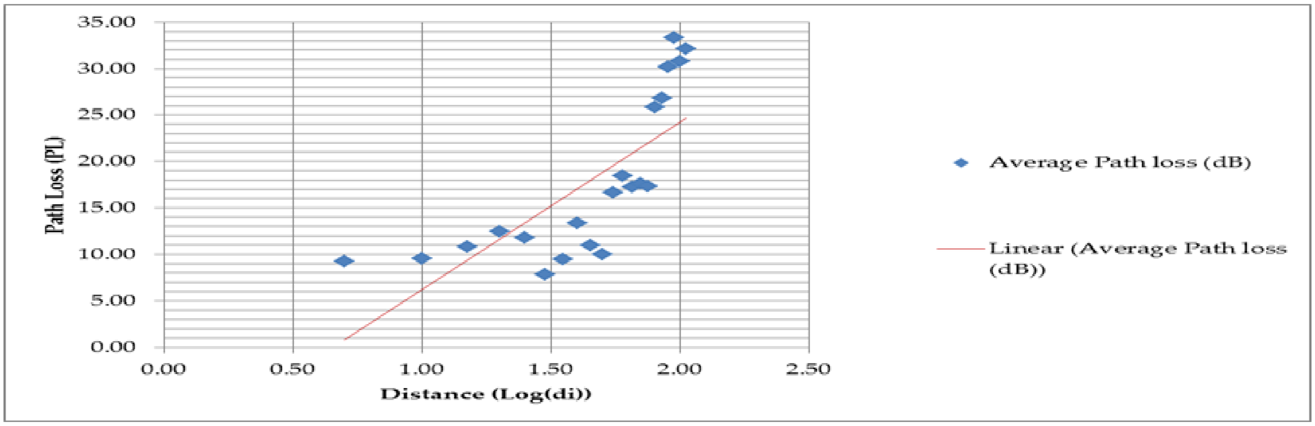


Figure 5.5. Curve fitted measurement data (Building5).

### E. Building6

This building has narrow and shorter corridors and limited open spaces with considerable obstructions. Measurements are done at twenty four data points at all floors of the building and the measured average path loss is indicated in Table5.6. The model parameters, and are computed as -12.62 and 20.87 respectively and the tuned model for this building is determined as:

$$PL(d) = -12.62 + 20.87\log(d) \tag{5.6}$$

The path loss exponent and RMSE are determined as 2.09 and 1.50dB respectively. The path loss exponent is higher than the path loss exponent of the other buildings and free space path loss; this can be mainly due to the considerable amount of clutter density in the area.

| Data Points | Distance from the reference point (m) | Log(di) | Average Path loss (dB) |
|---|---|---|---|
| 1 | 5 | 0.70 | 3.72 |
| 2 | 10 | 1.00 | 8.26 |
| 3 | 15 | 1.18 | 11.23 |
| 4 | 20 | 1.30 | 15.35 |
| 5 | 25 | 1.40 | 14.05 |
| 6 | 30 | 1.48 | 18.34 |
| 7 | 35 | 1.54 | 22.24 |
| 8 | 40 | 1.60 | 22.33 |

Table 5.6. Measured average path loss for Building6.

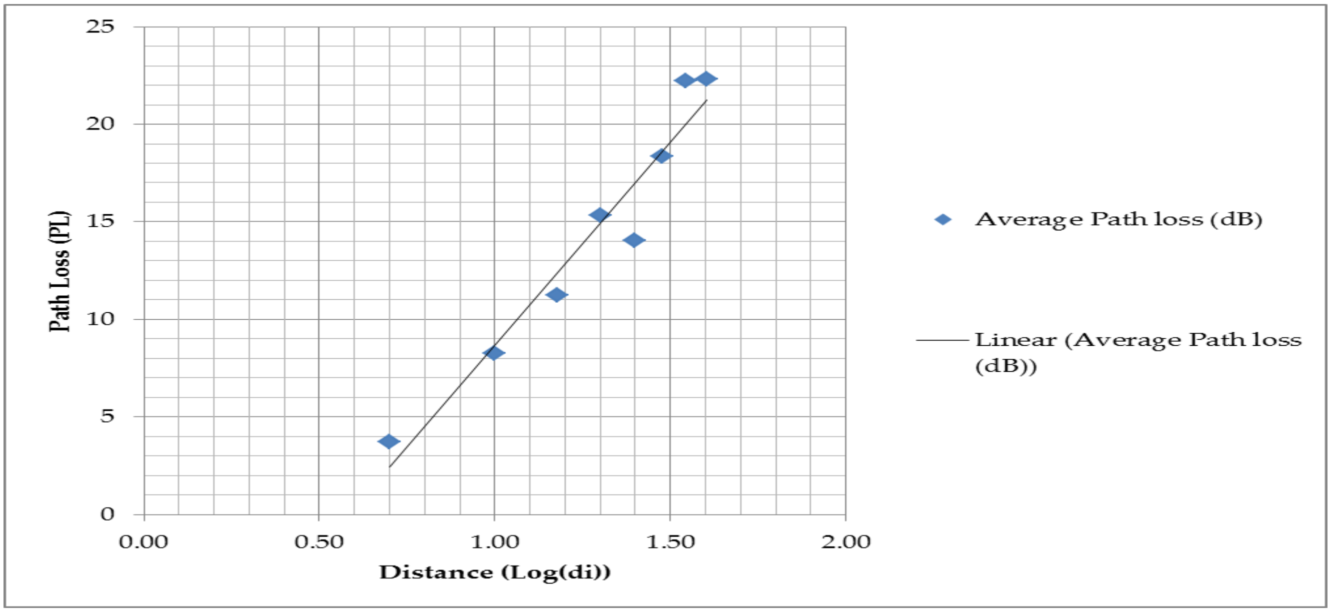


Figure 5.6. Curve fitted measurement data (Building6).

### 5.4.2. Log-normal shadowing model

Log normal shadowing model tuning is handled in the same manner as PLS model except considering $X_\sigma$ which has been given in Equation 3.5 and expresses the typical deviation $\sigma$ in dB. After adding the deviation to the remaining part of the equation tuned log-normal shadowing model is determined for each building. The result is summarized in Table5.7.

| **Building** | **Tuned Model** | **RMSE (dB)** |
|---|---|---|
| Building1 | $\boxed{PL(d) = 6.64 + 8.71\log\left(\frac{d}{d_0}\right)}$ | 1.38 |
| Building3 | $\boxed{PL(d) = -0.67 + 16.36\log\left(\frac{d}{d_0}\right)}$ | 2.88 |
| Building4 | $\boxed{PL(d) = 8.05 + 5.15\log\left(\frac{d}{d_0}\right)}$ | 4.43 |
| Building5 | $\boxed{PL(d) = -6.31 + 18.06\log\left(\frac{d}{d_0}\right)}$ | 5.25 |
| Building6 | $\boxed{PL(d) = -10.67 + 20.87\log\left(\frac{d}{d_0}\right)}$ | 1.41 |

Table 5.7. Tuned log-normal shadowing model.

### 5.4.3. Indoor environment analysis

The indoor environment of the investigated buildings can be roughly categorized as buildings that have relatively narrow corridors and open spaces without or with few obstructions; those building that have relatively narrow corridors and open spaces with considerable obstructions and buildings that have relatively wide and long corridors and open spaces with some clutters. Partitions of the rooms of the buildings are mainly made from hollow concrete blocks, aluminum and glasses.

In general buildings that have narrow corridors and open spaces without or with few clutters have lesser path loss exponent ($n$) compared to other buildings and free space path loss exponent.

In the other hand, buildings that have wide and long corridors and open spaces with light clutter density have greater path loss exponent ($n$).

As it can be observed from Figure 5.7, Figure 5.8 and RMSE values, radio propagation path loss in buildings that have relatively narrow corridors and open spaces with no or few clutters is better represented by PLS model.

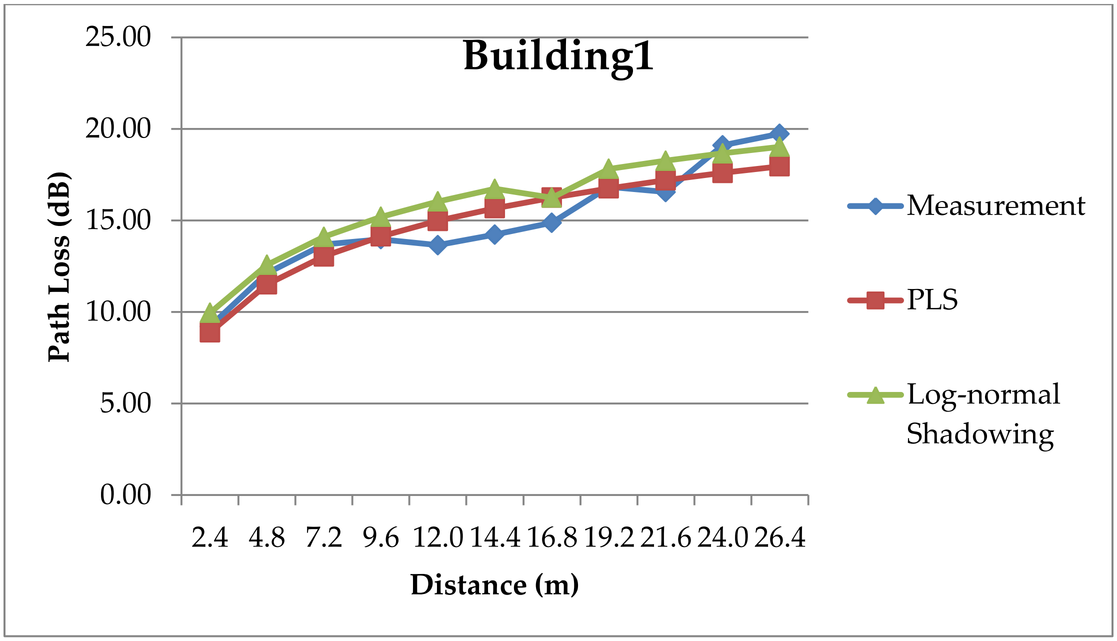


Figure 5.7. Measured and predicted path loss values (Building1).

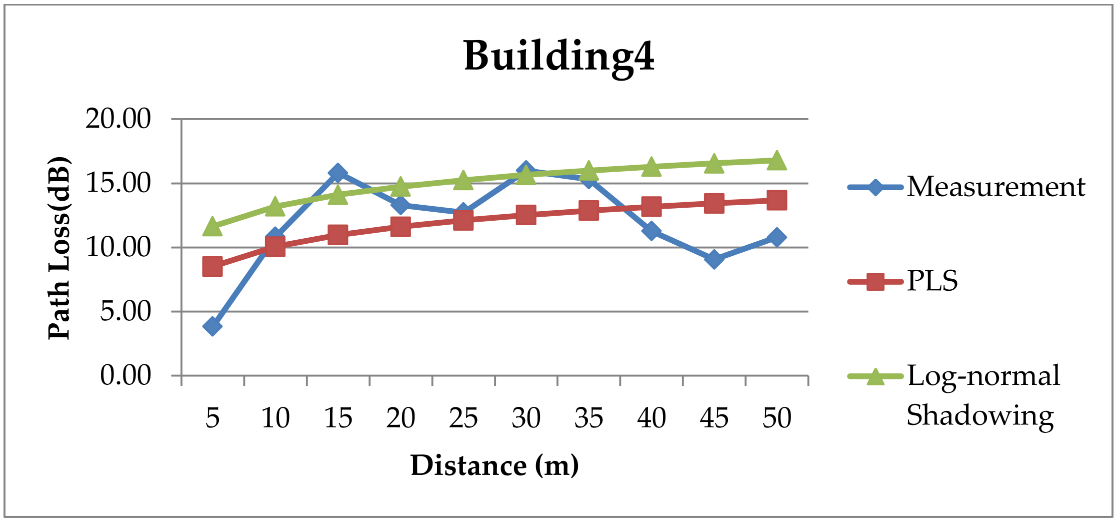


Figure 5.8. Measured and predicted path loss values (Building4).

On the other hand, as indicated in Figure 5.9 and from RMSE values, the propagation path loss of narrow corridor buildings with considerable clutter density and propagation path loss of some buildings with wide and long corridors and open spaces are better represented by Log-normal shadowing model.

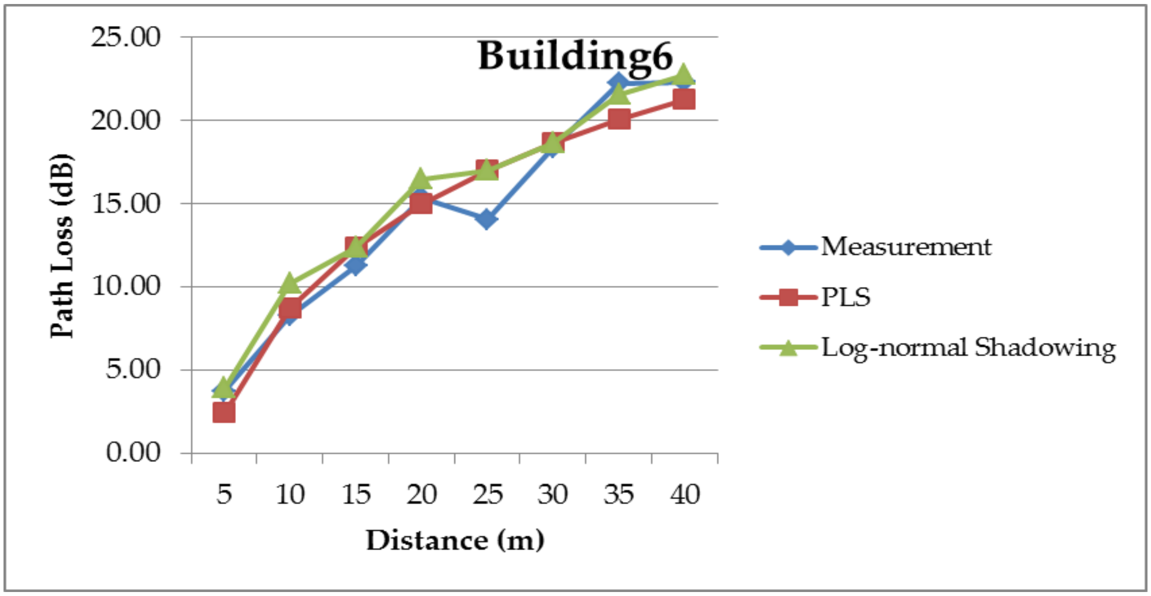


Figure 5.9. Measured and predicted path loss values (Building6).

## 5.5. Proposed models based on tuned models

PLS and log-normal shadowing models which are tuned based on relative average path loss measurement in the indoor environment are intended to represent the indoor path loss component of the total outdoor-to-indoor radio propagation path loss.

Based on the indoor environment of buildings, either the tuned PLS or log-normal shadowing models can be combined with a selected outdoor propagation model and building penetration loss to characterize and capture the total outdoor-to-indoor propagation path loss.

$$PL(d) = Outdoor\,\mathrm{mod}\,el + BPL + PLS \,/\, Log - normal \qquad (5.7)$$

The tuned indoor models can also be used for dedicated indoor solution dimensioning. Summary of model parameters of PLS and Log-normal shadowing is given in Table5.8.

| Buildings | Indoor enviroment description | n | RMSE | |
|---|---|---|---|---|
| | | | PLS | Log-normal |
| Building1 | Relatively narrow & free corridors (less than 2m wide) | 0.87 | 1.06 | 1.38 |
| Building3 | Relatively wide and open corridors (greater than 4m wide) | 1.64 | 2.04 | 2.88 |
| Building4 | Relatively narrow & free corridor (less than 2m wide) | 0.52 | 3.13 | 4.43 |
| Building5 | Relatively wide and long corridor (more than 4m wide and 105m long) | 1.81 | 5.53 | 5.25 |
| Building6 | Relatively narrow corridors with considerable clutters | 2.09 | 1.5 | 1.41 |

Table 5.8. Model Parameters summary.

# Chapter 6

# 6. Conclusion and future works

## 6.1. Conclusion

Indoor environment is becoming major source of mobile traffic as a result it is requiring more and more radio planning effort. This thesis has contributed to this effort by closely investigating, optimizing and suggesting outdoor-to-indoor propagation path loss model that can serve different categories of indoor environment. In this process BPL for buildings made from different materials has been determined for three commonly used frequency bands. Two commonly used indoor propagation path loss models have been tuned based on measurement data. Outdoor-to-indoor propagation models have been suggested as combination of outdoor models, penetration losses and the optimized indoor models.

It has been observed that BPL depends on building material types and frequency bands. But it is not possible to conclude that whether the building penetration loss increases or decreases with frequency. The identified building penetration losses can be considered in radio planning exercise as useful penetration loss margin.

The tuned PLS model better performs in most of the investigated indoor environment categories such as buildings with narrow corridors and open spaces with less or no obstructions and buildings with wide corridors and open spaces with very light clutter density. On the other hand log-normal shadowing has better or comparable accuracy in predicting path loss in buildings with considerable clutter density.

## 6.2. Future work

There are several areas that can be considered as future work that will be extended from this thesis.

BPL can be better investigated by isolating the building material and performing the measurement using dedicated test transmitters and receivers. As part of the investigation in addition to penetration loss across the walls, floor penetration loss can also be considered. The study can also be extended by adding more frequency bands and building materials. Additional parameters such as transmitter to receiver distance and signal incident angle can also be considered.

Empirical outdoor-to-indoor and indoor propagation models that need dedicated and movable test transmitters can be considered as future work. For more accurate propagation models, specifically large buildings with big number of indoor users, it is useful to consider deterministic and semi-deterministic propagation models. Radio propagation characteristics across many walls and floors can further be studied and modeled for specific indoor environments.

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