Measurement Based Statistical Model for Path Loss Prediction for Relaying Systems Operating in 1900 MHz Band

Masoud Dao Hamid

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Measurement Based Statistical Model for Path Loss Prediction for Relaying Systems Operating in 1900 MHz Band

by

Masoud Dao Hamid

A dissertation submitted to the College of Engineering at Florida Institute of Technology in partial fulfillment of the requirements for the degree of

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Melbourne, Florida December 2014
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"Measurement Based Statistical Model for Path Loss Prediction for Relaying Systems Operating in 1900 MHz Band,"

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Abstract

Measurement Based Statistical Model for Path Loss Prediction for Relaying Systems Operating in 1900 MHz Band

by

Masoud Dao Hamid

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Relays play important role in deployment of Long Term Evolution (LTE) and LTE-Advanced systems. They are used to enhance coverage, throughput and system capacity. The impact of the relay deployment on the network planning has to be modeled so that the above mentioned goals can be achieved. For successful modeling one needs to predict the path loss on the link between an eNodeB and a relay station. The review of literature shows that there is a general shortage of measured data to help empirical understanding of the propagation conditions in relay environment. This dissertation aims at developing empirical path loss models for relaying systems operating in 1900 MHz frequency band.

The path loss models are derived on a basis of an extensive measurement campaign conducted in a typical suburban environment. The path loss modeling takes into account the impact of the relay antenna height and therefore, an antenna height correction factor is derived and included in the modeling. The parameters of
those empirical models include the slope \((m)\) and the intercept \((PL_0)\) for each level of the examined relay heights. The parameters are determined from empirical studies and through the appropriate linear regression process. In addition to path loss modeling, the validity of some commonly used propagation models is evaluated by comparing their predictions to the measurements.

It was found that the path loss may be modeled successfully with a slightly modified log-distance propagation model. Two new different approaches for development of the statistical propagation path loss models for relay systems has been accomplished. The first approach includes fixed slopes and intercepts along with a distance dependent antenna height correction. The second approach does not include the relay antenna height correction factor but the height of the relay antenna becomes part of the slope and intercept calculation. For both approaches, the results show that model predictions are in good agreement with the measurement. As far as the validity of the commonly used models is concerned, the comparison to the measurements reveal that the applicability of those models for relaying environment is still debatable. Some modifications are introduced in order to improve the performance of these models. With the proposed correction factors all the examined models perform adequately and with approximately the same accuracy.
Table of Contents

Chapter 1: Introduction .................................................................................. 1
  1.1 Motivation...................................................................................................... 1
  1.2 Objectives ..................................................................................................... 3
  1.3 Dissertation Outline.................................................................................... 4

Chapter 2: Literature Review .......................................................................... 6
  2.1 Suggested Propagation Models for Relaying Scenarios.............................. 7
  2.2 Impact of Receiver Antenna Height............................................................. 7

Chapter 3: Relaying ......................................................................................... 13
  3.1 Motivation for Relaying ................................................................................ 13
  3.2 Concept of Relaying..................................................................................... 16
  3.3 Classifications of Relays ............................................................................. 17

Chapter 4: Background on Propagation Models .......................................... 19
  4.1 Introduction.................................................................................................. 19
  4.2 Basic Propagation Mechanisms .................................................................. 20
  4.3 Propagation Models..................................................................................... 22
    4.3.1 Basic Propagation Models .................................................................... 23
      4.3.1.1 Free Space Model............................................................................ 23
4.3.1.2 Tow-Ray Model ............................................................... 26
4.3.2 Deterministic Models.......................................................... 27
4.3.3 Statistical Models ............................................................... 28
  4.3.3.1 Log Distance Path Loss Model ..................................... 29
  4.3.3.2 Lee Model .................................................................. 31
  4.3.3.3 Hata Model ................................................................ 33
  4.3.3.4 COST-231 Model ......................................................... 34
  4.3.3.5 IEEE 802.16j Channel Model ........................................ 35
  4.3.3.6 WINNER II Model ....................................................... 39
  4.3.3.7 3GPP models ............................................................... 40
  4.3.3.8 New relaying model ..................................................... 46

Chapter 5: Development of Propagation Model for Relay Stations ....... 48
  5.1 Measurement Environment ................................................... 48
  5.2 PCS Frequencies ................................................................. 49
  5.3 Developing the Link between Relay Model and Existing Models .... 50
  5.4 Mathematical Modeling ......................................................... 51

Chapter 6: Measurement System and Procedure .............................. 57
  6.1 Equipment Description ......................................................... 57
    6.1.1 Transmitter .................................................................. 57
    6.1.2 Transmit antenna .......................................................... 58
    6.1.3 Antenna Pattern ........................................................... 59
6.1.4 Receiver .................................................. 63
6.1.5 Receive antenna........................................... 65
6.1.6 Software .................................................. 66
6.2 Receiver Noise Floor and Noise Figure ......................... 68
6.3 Spectrum Clearing........................................... 70
6.4 Procedure .................................................. 72

Chapter 7: Path Loss Measurements for Relay Stations .......... 80
7.1 Performance Analysis of Path Loss Measurements ............. 80
7.2 Path Loss Models at Different Relay Antenna Heights .......... 89
7.3 Received Signal Level models for Relay Stations ............... 91
7.4 Path Loss Differences for the Examined Relay Heights ......... 95
7.5 Relay Antenna Height Correction Factor ......................... 100
  7.5.1 For the case $h_{ref}=4$ m: .................................. 111
  7.5.2 For the case $h_{ref}=1.7$ m: .................................. 120

Chapter 8: Developed Path Loss Models for Relaying Systems ....... 123
8.1 Performance Analysis of Existing Models ....................... 123
  8.1.1 Corresponding Assumptions for Considered Models .......... 124
  8.1.2 Simplified Versions of Existing Models .................... 126
  8.1.3 Graphical and Statistical Evaluation ....................... 130
  8.1.4 Individual Evaluation of Existing Models ................... 135
8.2 Tuning of Existing Models ................................... 139
8.2.1 Tuning of Standard Models......................................................... 140

8.2.2 Tuning of Existing Relaying Models............................................ 142

8.3 Performance Analysis of Tuned Models ........................................... 145

Chapter 9: Conclusions and Future Work ............................................. 147

9.1 Summary and Conclusions ................................................................. 147

9.2 Future Work ...................................................................................... 149

Appendix: Antenna Pattern Data ............................................................ 151

References ............................................................................................. 157
List of Figures

Figure 3.1: Resolving lack of coverage by using relays ................................. 15
Figure 3.2: Three-node relay model .................................................................. 16
Figure 4.1: Propagation mechanisms .................................................................. 21
Figure 4.2: Two-Ray model ............................................................................... 26
Figure 4.3: Path loss vs. distance of 3GPP model for LOS and NLOS ................. 42
Figure 4.4: LOS probability as a function of distance for different environments.. 43
Figure 4.5: Path loss of 3GPP model considering LOS probability for urban
environment ........................................................................................................ 44
Figure 4.6: Path loss of 3GPP model considering LOS probability for suburban
environment ........................................................................................................ 45
Figure 4.7: Path loss of 3GPP model considering LOS probability for
suburban/rural environment ............................................................................... 45
Figure 6.1: Transmitter ...................................................................................... 58
Figure 6.2: Transmit antenna ............................................................................ 58
Figure 6.3: Azimuth antenna pattern in polar coordinates .............................. 60
Figure 6.4: Elevation antenna pattern in polar coordinates .......................... 61
Figure 6.5: Elevation antenna pattern in Cartesian coordinates .................. 62
Figure 6.6: Receiver ......................................................................................... 64
Figure 6.7: Receive antenna .............................................................................. 66
Figure 6.8: Power measurements: numerical display ........................................... 67
Figure 6.9: Power measurements: graphical display ........................................... 68
Figure 6.10: Spectrum clearing measurement system ........................................... 70
Figure 6.11: Signal strength measurements at frequency 1925 MHz for 24 hours ..... 72
Figure 6.12: Illustration of the base station ....................................................... 74
Figure 6.13: Illustration of the mobile and relay stations ..................................... 75
Figure 6.14: Illustration of the receiver on a boom-lift ....................................... 76
Figure 6.15: Map of the area where the measurements were conducted. Transmitter
location is – Latitude: 28.064° N, Longitude: 80.624° W .................................... 77
Figure 6.16: Measurement system .................................................................... 78
Figure 7.1: Received signal level by latitude and longitude .................................. 82
Figure 7.2: Measured and predicted path loss for different relay heights .......... 83
Figure 7.3: Distribution of prediction error for $h=1.7$ m ................................. 87
Figure 7.4: Distribution of prediction error for $h=4$ m ..................................... 87
Figure 7.5: Distribution of prediction error for $h=8$ m ..................................... 88
Figure 7.6: Distribution of prediction error for $h=12$ m ................................... 88
Figure 7.7: Distribution of prediction error for $h=16$ m ................................... 89
Figure 7.8: Measured and predicted received signal level for different relay heights
......................................................................................................................... 93
Figure 7.9: Distribution of path loss differences (PL($h=4$) - PL($h=8$)) .............. 96
Figure 7.10: Distribution of path loss differences (PL($h=4$) - PL($h=12$)) ........... 97
Figure 7.11: Distribution of path loss differences (PL(\(h=8\)) - PL(\(h=12\))) ..........97
Figure 7.12: Distribution of path loss differences (PL(\(h=8\)) - PL(\(h=16\))) ..........98
Figure 7.13: Distribution of path loss differences (PL(\(h=12\)) - PL(\(h=16\))) ..........98
Figure 7.14: Distribution of path loss differences (PL(\(h=4\)) - PL(\(h=16\))) ..........99
Figure 7.15: Distribution of path loss differences (PL(\(h=1.7\)) - PL(\(h=4\))) ..........99
Figure 7.16: Average relay antenna height correction factor (\(\Delta h_m\)) for \(h_{ref}=1.7\) m 102
Figure 7.17: Average relay antenna height correction factor (\(\Delta h_R\)) for \(h_{ref}=4\) m . 102
Figure 7.18: Path loss models based on the average relay antenna height correction factor for \(h_{ref}=1.7\) m ........................................................................................................ 104
Figure 7.19: Path loss models based on the average relay antenna height correction factor for \(h_{ref}=4\) m ........................................................................................................ 105
Figure 7.20: Prediction error based on the average relay antenna height correction factor (\(\Delta h_m\)) for \(h_{ref}=1.7\) m ........................................................................................................ 106
Figure 7.21: Prediction error based on the average relay antenna height correction factor (\(\Delta h_R\)) for \(h_{ref}=4\) m........................................................................................................ 107
Figure 7.22: Illustration of \(\Delta h\) as a function of relay height and distance .......... 109
Figure 7.23: Relay antenna height correction factor (\(\Delta h\)) as a funtion of distance and relay height........................................................................................................ 113
Figure 7.24: Measurements compared to model predictions after implemention of \(\Delta h\) for \(h_{ref}=4\) m ........................................................................................................ 115
Figure 7.25: Intercept (\(PL_0\)) as a function of relay antenna height................. 118
Figure 7.26: Slope \((m)\) as a function of relay antenna height

Figure 8.1: Comparison of model predictions with measurements for \(h=4\) m

Figure 8.2: Comparison of model predictions with measurements for \(h=8\) m

Figure 8.3: Comparison of model predictions with measurements for \(h=12\) m

Figure 8.4: Comparison of model predictions with measurements for \(h=16\) m
List of Tables

Table 1.1: Important LTE-Advanced parameters .................................................. 2
Table 4.1: Path loss exponent for different environments [35] .............................. 30
Table 4.2: Standard deviation for different environments ................................. 31
Table 4.3: Intercept and slope values for different environments ..................... 32
Table 4.4: Path loss types for IEEE802.16j relay system .................................. 36
Table 4.5: Parameters for the terrain type A/B/C ................................................. 38
Table 4.6: Standard deviation for different categories ........................................ 38
Table 4.7: Sub-scenarios of WINNER B5 model ............................................... 39
Table 4.8: LOS probability for different environments [8] .................................. 43
Table 4.9: Summary of path loss models and their restrictions ...................... 47
Table 5.1: The electromagnetic spectrum ........................................................... 49
Table 6.1: Transmit antenna technical specifications .......................................... 59
Table 6.2: Elevation angle and corresponding antenna gain .............................. 63
Table 6.3: Receiver inputs and their frequency ranges ....................................... 64
Table 6.4: Technical specifications of receive antennas ..................................... 65
Table 6.5: Parameters associated with the measurement campaign ................. 77
Table 7.1: Relay path loss propagation model parameters ............................. 85
Table 7.2: Relay received signal level parameters ............................................. 92
Table 7.3: Average of path loss differences between relay heights ................. 96
Table 7.4: Slope and intercept differences for $h_{ref}=4$ m ........................................... 110
Table 7.5: Slope and intercept differences for $h_{ref}=1.7$ m ........................................... 111
Table 7.6: Model comparison before and after implementation of $\Delta h$ relative to the measurements for $h_{ref}=4$ m ........................................................................................................ 116
Table 7.7: Comparison between measurements and model predictions ...................... 119
Table 7.8: Model comparison before and after implementation of $\Delta h$ relative to the measurements for $h_{ref}=1.7$ m ........................................................................................................ 122
Table 8.1: Models parameters assumptions for measurement campaign ..................... 127
Table 8.2: Comparison between measurements and models' predictions .................. 134
Table 8.3: Comparison between measurements and tuned-models' predictions ... 146
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Dedication

To:

My father and mother for their love, prayers, endless support and encouragement

My wife for her love, support, encouragement, patience and understanding

My kids for their love

My brothers, sisters, uncles and friends for their love and support

In memory of my grandmother for being my first teacher
Chapter 1: Introduction

1.1 Motivation

The number of mobile cell phone users is increasing at the rapid pace. The annual growth of data traffic is estimated to remain high. The global mobile data traffic is expected to increase at the rate of 61% from 2013 to 2018 [1]. The number of mobile-connected devices is expected to exceed the world population by the end of 2014 as reported in [1, 2]. This is due to user mobility and the ease of installations of wireless communication systems. WiFi, WiMAX, 3G and 4G cellular networks are some examples of cellular systems experiencing very high growth. Current 3G systems are not capable of providing very high data rate to a large number of users. Thus, there is a need for wireless access systems that can accommodate such growth. Currently, the Third Generation Partnership Project Long-Term Evolution (3GPP-LTE) and 3GPP-LTE-Advanced are being rolled out by many operators to meet ever increasing demand for higher data rate and better Quality of Service (QoS) [3].

LTE-Advanced is the upcoming global cellular technology that offers very high throughput on air its interface. The envisioned data rates for 4G LTE wireless systems can exceed 300 Mbps in the downlink (DL) and 75 Mbps in the uplink (UL) within 20 MHz of paired spectrum. LTE-Advanced, on the other hand, is set
to provide data rate up to 1 Gbps and 500 Mbps in down link and uplink, respectively [4]. Those high data rates are to be met by aggregating multi carriers with scalable spectrum up to 100 MHz. In order to get this very high data rate, high modulation schemes such as 16 QAM (Quadrature Amplitude Modulation) and 64 QAM need to be used. Table 1.1 summarizes important requirements for performance of the LTE-Advanced [5].

<table>
<thead>
<tr>
<th>Table 1.1: Important LTE-Advanced parameters</th>
</tr>
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<tbody>
<tr>
<td><strong>Peak data rate (Gbps)</strong></td>
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<td><strong>Peak spectrum efficiency (bps/Hz)</strong></td>
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<td><strong>Average spectrum efficiency (bps/Hz/cell)</strong></td>
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<td><strong>Cell edge user throughput (bps/Hz/cell/user)</strong></td>
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<tr>
<td><strong>Mobility</strong></td>
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<td>up to 500 km/h</td>
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<tr>
<td><strong>Bandwidth</strong></td>
</tr>
<tr>
<td>scalable bandwidth up to 100 MHz</td>
</tr>
<tr>
<td><strong>Modulation scheme</strong></td>
</tr>
<tr>
<td>QPSK, 16 QAM and 64 QAM</td>
</tr>
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</table>

One of most promising technology that helps LTE-Advanced meet these requirements is the use of relays. Within LTE and LTE-Advanced, radio relays are
used to extend coverage, enhance capacity, increase throughput and provide overall increase in the network performance [6-8]. In addition to performance enhancements, relays are expected to be a viable cost efficient solution for replacement of base stations [9,10]. When deployed, relays act like base stations but without the need of wired connection to the backhaul. From the network planning perspective one needs to be able to successfully model the impact of the relay deployment within an LTE network. The first step in this modeling is the prediction of the path loss on the link between the eNodeB and a relay station. The review of literature shows that there is a general shortage of measured data collection and understanding of the propagation conditions in relay environment. The measurement campaign discussed in this dissertation is set up specifically to evaluate the path loss encountered on eNodeB-relay link.

1.2 Objectives

The main objective of the research proposed in this dissertation is to develop statistical path loss models for outdoor relaying systems in 1900 MHz frequency band. The proposed models are derived to predict the radio signal path loss on the link between eNodeB and relay stations (backhaul link). The path loss modeling takes into account the impact of the relay antenna height and therefore, an antenna height correction factor is included in the modeling. The models are based on field measurements conducted in suburban environment. Two major contributions are achieved. Firstly, propagation models are derived by conducting comprehensive
measurements and explaining the behavior of the path loss as a function of relay station antenna height. Additionally, since many propagation models are already coded and part of software packages that are used for deployments, it is of special interest to establish a relationship between measurements and some of these standard propagation models. Well known examples of the standard models are: Hata-Okumura, Lee model, COST 231-Hata, COST 231 Walfisch-Ikegami, and many other proprietary models. Application of standard propagation models for modeling relay scenarios is examined and the appropriate correction factors are derived.

1.3 Dissertation Outline

The dissertation is organized as follows. Chapter 2 provides a summary of related work on path loss propagation models for relaying scenarios. Overview of the concept of relaying and classification of relays are given in Chapter 3. General background on propagation models and basic propagation mechanisms are provided in Chapter 4. Chapter 5 presents the development of propagation models for relay stations. In this chapter, developing the link between relay model and other existing models is introduced. Empirical relay model derivation is then provided. Chapter 6 is devoted to description of the procedure and equipment used in the measurement campaign presented in this document. Chapter 7 proposes propagation path loss models for eNodeB-relay link for multiple relay antenna heights, provides statistical analysis for the proposed models and introduces a relay
antenna height correction factor. Chapter 8 presents the evaluation of the existing models relative to the measurements, introduces some modifications of the original forms of the existing models to make their prediction more reliable in relaying environments. Finally, summary and some conclusions are drawn in Chapter 9.
Chapter 2: Literature Review

The concept of relaying (multi-hop) is not new. A classical three-node relaying model was first introduced in early 1970's [11]. A simple relay channel was proposed and an achievable lower bound to the capacity was established [12]. However there was no additional investigative study most likely because of non-foreseeable applications at that time. Recently, the concept of relays has been brought up again and proposed in the cellular network system such as WiMAX and 3GPP LTE-Advanced [13].

When deployed, relaying cellular networks consist of three links: BS-RS (Base Station-Relay Station) link, BS-MS (Base Station-Mobile Station) link and RS-MS (Relay Station-Mobile Station) link. These three links are also referred to as backhaul link (the link between eNodeB and relay), direct link (the link between eNodeB and end user) and access link (the link between relay and end user), respectively. The work presented in this dissertation focuses on the path loss evaluation encountered on eNodeB-relay link only. Backhaul link path loss and, in particular, the impact of relay station antenna height on propagation link in suburban areas need to be well understood so proper design can be offered for such networks.
2.1 Suggested Propagation Models for Relaying Scenarios

Whereas propagation models for BS-MS link have been widely studied in the literature (Okumura, Hata, COST 231 and Lee models, just to name a few), far too little attention has been paid to the BS-RS link. To this end, some of propagation models have been suggested by 3GPP (3rd Generation Partnership Project) [8], WINNER (Wireless World Initiative New Radio) [14] and IEEE 802.16j task group [15]. Nonetheless, one general limitation of these models is that they are developed from already existing propagation models that were derived under completely different assumptions. Hence their applicability to relay scenarios need to be examined. Another limitation is that the considered models were derived for just certain levels of relay antenna height. Models in [8] and [14] were derived for relay heights 5 m and 15 m, respectively, and therefore their validation for multiple relay heights still needs to be performed.

2.2 Impact of Receiver Antenna Height

The impact of mobile station antenna height on the propagation channel of BS-MS link has been extensively studied in [16-19]. In these studies, typical mobile station antenna height was about 0.3-3 meters. Research on the effect of relay station antenna height on BS-RS propagation link, on the other hand, has not yet been adequate. To the best of author's knowledge, very view studies evaluate
the path loss on the eNodeB-relay link (BS-RS link) for different relay heights. In this section, related work will be reviewed.

Quang Hien, *et al.* in [20] investigated the effect of receive antenna height on the received signal level in a LTE-Advanced relaying scenario. The study concentrated basically on the BS-RS link only. In this study, multi-frequency bands were used and measurements were conducted in an urban environment. The measurements were performed by locating the receiver in different positions in a multi-floor building. The aim of using a multi-floor building is to represent different levels of receiver antenna height. The obtained results show that higher received signal levels are achieved for higher relay antenna heights. WINNER B5a and B5f models for relaying scenarios were examined. Authors claimed that whereas their results were in agreement with WINNER B5a model, disagreement was pronounced comparing to WINNER B5f model. Study would have been more interesting if the authors had proposed an empirical path loss model which can be applied in similar scenarios.

Similar to the work done in [20], authors in [21] studied the impact of relay antenna height on LTE-Advanced path loss channel model focusing on the BS-RS link. Measurements of path loss values were performed at three levels of relay antenna height. The experiments were carried out at frequency of 2.1 GHz in an urban macro-cellular area. As expected, dependency of path loss on relay antenna
height was observed. The obtained path loss values decrease with the increase of relay antenna height. Various existing propagation models, which could be applied for BS-RS link, were then examined. Authors reported that the most striking result to emerge from the data comparison was that the disagreement between the obtained results and the IEEE 802.16j model was very obvious and on the order of approximately 20 dB. Another pronounced mismatch was with WINNER B5f model. These results were surprising because both IEEE 802.16j and WINNER B5f models were proposed for relaying scenarios. A third interesting observation from the study was that even though COST-231 Walfish-Ikegami model was not designed for relaying deployment, it provided the closest results of path loss prediction when compared to other models that were examined. Finally, a simple statistical propagation model for relaying scenarios which takes into consideration the influence of the relay antenna height was suggested. Nevertheless, studies in [20, 21] conclude that the validity of the investigated models which were designed for relaying systems is questionable.

Unlike [20] and [21], the study presented in [22] not only investigated the impact of relay station antenna height on the received signal power of BS-RS link but also analyzed the corresponding Signal to Interference Ratio (SIR). The study included also the effect of the relay station antenna type i.e. (directional versus omnidirectional configuration) on the BS-RS link performance. Results in this study were based on data collected in a real urban macro-cell area operating in 3G
network deployment. Authors concluded that both relay station antenna height and type affect the BS-RS link performance. Although increasing relay station antenna height results in better received signal, using directional antenna to improve SIR has a significant impact only in Line of Sight (LOS) conditions. Nevertheless, the major concern of this study was the performance evaluation of the relay station location rather than studying the propagation path loss models in the BS-RS link.

Authors in [23] provided new statistical propagation models for peer-to-peer communication channel. Five links, namely, BS-MS, BS-RS, RS-RS, RS-MS and MS-MS were considered. Models were developed based on measurements performed in center of Bristol, UK. This study has shown that the path loss decreases with higher antenna heights and with higher probability line of sight. The study has gone some way towards enhancing the understanding of dependency of shadowing and LOS probability on distance. However, the main focus of this study was on peer-to-peer (MS-MS) links which have low antenna heights and short distances.

Work in [24] presented measurements conducted in relay-deployed network in an urban environment at frequency 3.5 GHz. BS-RS link path loss was analyzed and compared to COST 231 and IEEE 802.16d models. Authors found out that results of BS-RS link are in agreement with IEEE 802.16d. However, the
maximum height of relay station antenna was limited to 5 meters which is too low for most relay scenarios.

In [25], comparison between different propagation models were made at two levels of receiving antenna height. Unlike studies [20-24], where the measurements were carried out in urban environment only, work presented in [25] investigated the path loss in different environments. However, this study does not take in account some propagation models proposed for relaying scenarios such as 3GPP and WINNER.

Related work is to be found in [26]. Even though a statistical path loss model was developed in this work, the receiver antenna height ranged only between 3 to 7 meters which is low according to proposed relay scenarios [8, 14].

Other work reported in [27, 28] considered a receiver antenna height up to 10 meters. Nevertheless, these studies neither suggest new propagation models nor provide comparison with any of the existing models.

Reference [18] analyzed the influence of changing the antenna heights of both transmitter and receiver on path loss models. However, this study concentrated on indoor channel characterization.

In short, a number of important limitations, that previous work suffer from, needs to be addressed. One major constrain is that the studied relay station antenna
heights considered to be low compared to proposed relay scenarios [8, 14]. Another limitation is that, in most studies, no statistical path loss models were proposed and if any, they were derived for urban environment and their validity for different environments such as suburban or rural areas is questionable. Third, the validity of the proposed models for relaying systems is still questionable and therefore, further studies are required to examine their applicability across variety of scenarios. Finally, in most of the related work, frequency bands that were used are different from the one that will be used in this study. Hence, there is a need to cover these gaps and this is the aim of the work described in this document.
Chapter 3: Relaying

3.1 Motivation for Relaying

As it was mentioned in chapter one, LTE-Advanced offers very high data rate on the air interface due to the use of high modulation schemes such as 16 QAM and 64 QAM. High modulation schemes require high Signal to Noise ratio (S/N). This is because for a given power level, the bit energy decreases if the data rate increases. It is also well known that for a given power the available data rate decreases with the increasing of distance between base station and mobile device. For instance, at cell edge the (S/N) is usually not high enough to use high modulation schemes and consequently to have high data rate. One solution is to increase the power of the base station so that the terminal at cell edge gets an improved (S/N). Unfortunately, from practical prospective this solution is not realistic. Increasing the power of one base station beyond certain level causes interference with other signals from surrounding cells (inter cell interference). Even if that would work for the down link (from base station to mobile station), it does not work for the uplink (from mobile station to base station) because mobile device has limited power. Therefore, to achieve high data rate, mobile station needs to be close to the base station. Hence, the use of a traditional cellular radio network would require a very high number of base stations to meet the required high data
rate. Unfortunately, adding more base stations results in potentially high deployment costs and it does not appear economically reasonable. In [29], it is shown that the deployment cost of a cellular radio network is directly proportional to the number of base stations.

It is apparent that a novel solution is necessary for the very ambitious throughput and coverage requirements of future systems. One of most promising solutions is the deployment of relaying (multi-hop) technology. It promises to reduce the deployment cost while enabling enhancement of coverage, throughput and system capacity [6, 7, 10, 13, 30-33]. Relaying technique is considered a viable solution for replacement of base stations. Relays cost significantly less than base stations. The relays act like base stations but without the need of wired connection to backhaul.

Relaying technique has been used typically for resolving the lack of signal coverage in some areas. Shadowed and dead spot areas, tunnels, in building, stadia and campus environments are some examples of low wireless signal areas. The technique is implemented where the traffic is too low to justify the deployment of a conventional base station. Relays can also be deployed to extend coverage where the signal is not sufficient to access the base station like at cell edge. Relays can provide temporary coverage in particular occasions such as sporting events, or in emergency and disaster situations. Furthermore, mobile relays can provide access
to subscribers in high speed motion scenarios such as in airplanes or trains. Figure 3.1 shows an example of a relay deployment to enhance or provide coverage in areas mentioned previously.

**Figure 3.1**: Resolving lack of coverage by using relays
3.2 Concept of Relaying

Figure 3.2 illustrates a simple three-node relay model. This model consists of a base station, relay station and mobile station. As shown in the figure, the mobile station can receive the signal from the base station through two different paths, the one-hop direct link or the two-hop relaying link. In the one-hop direct link, the path between the base station and the mobile station is called BS-MS link. In the two-hop relaying link, a multi-hop relaying system consists of two links. The first link is the link between the base station (eNodeB) and the relay station and it is referred to as the BS-RS link or (backhaul link). The second link is the link between the relay station and the mobile station (end user) and it is referred to as the RS-MS link or (access link).

![Figure 3.2: Three-node relay model](image-url)
Since the relay station communicates both with the base station and the mobile station, interference between the backhaul link and the access link may occur. In order to avoid this interference, isolation between the two links is required. Isolation can be achieved in several ways: frequency, time, and/or spatial domains [34].

### 3.3 Classifications of Relays

There are different ways to classify relays. With respect to the relay's usage of spectrum, relaying can be classified into *outband* and *inband* types. In outband relaying type, backhaul link and access link operate in a different carrier frequency. Therefore, interference between backhaul link and access link can be avoided by obtaining the isolation between the two links in frequency domain. This approach is referred to as *Frequency Division Multiplexing* (FDM). On contrary, in inband relaying type, both backhaul link and access link operate in the same carrier frequency. In this type of relaying, the isolation between the two links is obtained in time domain. This approach is referred to as *Time Division Multiplexing* (TDM).

Another way to classify relays is according to how relay processes the received signal. According to this approach, relays can be classified into *amplify-and-forward* and *decode-and-forward* relays [6]. The former one is commonly referred to as *analog repeaters* whereas the later one is referred to as *digital repeaters*. The first type simply receives signals including noise and interference,
amplifies and then forwards them. This type of relays is very simple and has very short processing time delay, but it also amplifies noise. Therefore, relays of this type are mainly useful in high-SNR environments. Decode-and-forward relays, on the other hand, decode and re-encode the received signal before forwarding it to users. This means that this type of relays forwards the useful signal only but not noise and interference. For that reason, decode-and-forward relays are useful in low-SNR environments too. However, the processing time in this type is longer which result into additional delay.
Chapter 4: Background on Propagation Models

4.1 Introduction

In wireless communication system signals travel between transmit antenna and receive antenna through a channel. The channel is a fundamental part of wireless system deployment and has an essential role of the system performance. In general, when the signal travels its level decreases with the increasing distance between source (base station, relay station or mobile station) and destination (mobile station, relay station or base station). The degradation in the transmitted signal power as it propagates in space is referred to as path loss. Prediction of the path loss is a fundamental task in cellular systems deployment. One of the requirements of designing base stations in cellular networks is to have a basic understanding of coverage areas of each base station. Finding the coverage area of each base station through measurement is impractical since it can be very expensive and time consuming process. Instead, engineers rely on propagation modeling that estimates the average signal strength and consequently the path loss at any particular distance from the base station. While overestimation of path loss can result in extensive coverage overlaps, an underestimation can lead to coverage holes. Path loss is a function of various factors such as free space losses,
diffraction, reflection, refraction, transmission frequency, terrain and many others. Numerous propagation models have been derived and studied, however; there is no single model can be applied for all the environments. As a result, the Quality of Service (QoS) of the whole cellular network depends on the selection of most suitable of the radio propagation model.

In this chapter some of the propagation mechanisms, namely, reflection, diffraction and scattering, which occur as a result of obstacles' presence, are briefly explained. Then, various propagation models which are used in assessing the performance of a wireless system will be presented.

### 4.2 Basic Propagation Mechanisms

Unlike free space where the signal propagates without any obstacles, in cellular mobile communication the signal is exposed to three basic effects:

*Reflection*: reflection occurs when a propagating wave impinges on an object which is very large compared to its wavelength. Typical examples of such kind of objects are surface of the earth, walls and buildings.

*Diffraction*: diffraction occurs when the path between the transmitter and the receiver is obstructed by an object that has sharp irregular edges. As a result, waves bend around and propagate behind the obstruction reaching the receiver even when
there is no LOS. This phenomenon is called shadowing because the receiver is located in a shadowed region.

Scattering: scattering occurs when objects are on the order or less of the wavelength of the radio signal. Typical examples of such kind of objects are street signs, foliage and lamp posts. When a radio signal reaches such objects, it scatters in many different directions. Figure 4.1 illustrates these three mechanisms.

![Figure 4.1: Propagation mechanisms](image)

As a mobile user moves throughout a coverage area, the instantaneous received signal power is subject to the above mentioned three mechanisms.
Multiple copies of the signal (multipath propagation) would be presented at the receiver and they may interfere constructively or destructively. Diffraction and scattering result in a small scale fading. It describes the rapidly variation in the instantaneous signal power when a mobile user moves over a short distance. On the other hand, reflection causes a large scale fading. It characterizes the signal variation over a larger distance. These variations are usually predicted by using propagation models by averaging the received signal level at a particular distance from the transmitter.

4.3 Propagation Models

One of the fundamental parameters of designing cellular communication systems is the received signal level. In order to predict the average received signal level, propagation models are used. In this regard, propagation modeling becomes a very significant tool to study. Signal attenuation (or path loss) prediction and received signal level prediction are two faces of the same coin. In other words, if one is able to predict the median path loss then the median received signal level is implicitly known. The path loss is simply the deference, expressed in decibels, between the transmitted signal and the received signal power. Path loss includes all possible losses which result from the free space propagation and other different propagation mechanisms. In general, it is also function of other parameters like antenna heights, carrier frequency, distance, environment type (urban, suburban or rural) ... etc. Models that are used for predicting the path loss in macro-cells, which
are usually encountered in cellular networks, are called *macroscopic propagation models*. There are many of them and they have different levels of accuracy and complexity. In general, there is a tradeoff between model simplicity and its accuracy. Macroscopic propagation models can be classified into three main categories: basic propagation models, statistical propagation models and deterministic models.

### 4.3.1 Basic Propagation Models

Basic propagation models are used to predict the path loss in a very simple way. These basic models, by their very nature, give an approximated value of path loss but they are introduced here to understand the other kinds of propagation models which will be discussed later.

#### 4.3.1.1 Free Space Model

The major assumption in free space propagation is that there is a clear line of sight (LOS) between transmitter and receiver, meaning that no obstructions exist. In other words, waves travel without reflection, diffraction, scattering, or any other mechanisms. This model is used to predict the received signal power at a particular distance. Satellite communication systems and microwave links are typical example of such kind of models. The received signal power $P_r$ at distance $d$ from the transmit antenna can be given as [35]:

$$P_r = P_t G_r G_t \lambda^2 / 4\pi d^2$$
\[ P_r = P_T \frac{G_{TX}G_{RX}}{(4\pi d/\lambda)^2} \]  

(4.1)

where

\begin{align*}
P_r & \quad - \text{Received power at distance } d \text{ from the transmitter} \\
P_T & \quad - \text{Transmit power} \\
G_{TX} & \quad - \text{Gain of transmitting antenna} \\
G_{RX} & \quad - \text{Gain of receiving antenna} \\
\lambda & \quad - \text{Wave length} \\
d & \quad - \text{Distance between the transmitter and receiver}
\end{align*}

The propagation loss is usually expressed in decibels (dB) and it is given by

\[ L[\text{dB}] = 10\log \left( \frac{P_T}{P_r} \right) \]  

(4.2)

Therefore,

\[ L[\text{dB}] = 10\log \left[ \frac{(4\pi d/\lambda)^2}{G_{TX}G_{RX}} \right] \]  

(4.3)

Since

\[ \lambda = \frac{c}{f} \]  

(4.4)

where
\( c \) - Light velocity in space \([3.10^8 \, m/sec]\)

\( f \) - Operating frequency

Substituting (4.4) in (4.3) one gets:

\[
L[\text{dB}] = 10 \log \left( \frac{(\frac{4\pi f d}{c})^2}{G_{TX} G_{RX}} \right)
\]  

\( L[\text{dB}] = -g_{TX} - g_{RX} + 20 \log(f) + 20 \log(d) + 20 \log(4\pi/c) \)  

Free space path loss, which represents the attenuation of the signal power, is defined as the difference in dB between the effective transmitted power and received power. When antenna gains are excluded, then the free space path loss \((PL_{FS})\) can be given as

\[
PL_{FS}[\text{dB}] = 32.44 + 20 \log(f) + 20 \log(d)
\]  

where now the frequency \( f \) is in units of MHz and distance \( d \) in units of Km. If \( d \) is expressed in miles then Eq. (4.6) can be written as:

\[
PL_{FS}[\text{dB}] = 36.5 + 20 \log(f) + 20 \log(d)
\]  

Equations (4.6) and (4.7) are called Friis equations [36]. It is noteworthy to observe that the free space path loss increases 20 decibel per decade of either
frequency or distance. In other words, free space path loss increases by 6 dB for each doubling in either frequency or distance.

4.3.1.2 Two-Ray Model

Unlike the free space propagation model where there is only a direct path between the transmitter and the receiver, here, as the name says, the received signal is sum of two components results from two different paths. First path is the direct or LOS path and the second one is the ground reflected path. Figure 4.2 illustrates this situation.

![Two-Ray model](image)

Figure 4.2: Two-Ray model

The formula of path loss for this model is expressed as [36]:

$$P_{loss} = 10 \log_{10} \left( \frac{4 \pi f}{c} \right)^2 d^2$$
\[ PL = 40 \log(d) - 20 \log(h_b) - 20 \log(h_m) \tag{4.8} \]

where,

\begin{itemize}
  \item \( d \): Distance between transmitter and receiver in meters
  \item \( h_b \): Height of the transmitter antenna in meters
  \item \( h_m \): Height of the receiver (mobile) antenna in meters
\end{itemize}

It is remarkable that the path loss here increases by 40 dB/dec as a function of distance or 12 dB by doubling the distance. It is also notable that the path loss depends on antenna heights of transmitter and receiver. The other observation that can be made here is that \( PL \) is frequency independent. One of the drawbacks of the two ray model is that it underestimates the path loss because of two major reasons. In practice, loss is almost always frequency dependent. Second, in this model the ground was assumed flat and smooth which is in reality not the case. As was mentioned earlier, the roughness of the terrain can lead to scattering which in turn affects the total value of the signal power and consequently the path loss.

### 4.3.2 Deterministic Models

These types of models estimate the propagation path loss analytically. They are based on physical laws of electromagnetic wave propagation. Deterministic models consider all the propagation mechanisms and they tend to be accurate. However, they are very complex because they require very large detailed data that
describe the propagation environment. Such data include all geometric information about all the obstructions involved. The computational effort involved might be massive or even beyond the capability of existing computers especially if the environment is large and/or complex [37]. A typical example of deterministic propagation models is a ray tracing model [38, 39].

4.3.3 Statistical Models

As it was mentioned in the previous section, deterministic models require very large amount of information about the environment in which models are applied. This is a very complex procedure. There is always a tradeoff between simplicity and accuracy. The accuracy of path loss prediction might not be the essential task of a wireless cellular system designer. The major concern here is the overall area covered rather than specific signal power at a particular location. To this end, statistical models are often more appropriate. Statistical propagation models are usually based on field measurements, therefore, they are also called empirical propagation models. In this type of models, extensive measurements of path loss are made, and through statistical analysis of the data collected appropriate equations are derived. Empirical models give satisfactory results when they are used in similar environments to the one where the measurements were made. One big advantage of such models is that they take into account all the propagation parameters. However, in order for them to be applicable in environments other than
those used for their derivations, correction factors need to be added. In the following some of the most popular empirical models are discussed.

4.3.3.1 Log Distance Path Loss Model

In general, the path loss at any particular location can be seen as consisting of three major components: loss due to distance between transmitter and receiver, log normal shadowing (large scale fading or slow fading) and small scale fading (fast fading). In the first order approximation, the predicted path loss in [dB] at any given distance \( d \) from the transmitter with respect to a reference distance \( d_0 \) may be described as log-distance path loss model and given by [35]:

\[
PL(d) \text{[dB]} = PL_0 + m \log \left( \frac{d}{d_0} \right)
\]  \hspace{1cm} (4.9)

where

\[
\begin{align*}
    d_0 & \quad \text{- Reference distance (usually 1km or 1 mile in macro-cells and 100 m in microcells)} \\
    PL_0 & \quad \text{- Path loss at the reference distance (intercept)} \\
    d & \quad \text{- Distance between transmitter and receiver} \\
    m & \quad \text{- Slope in [dB/decade] which can be given as:} \\
    & \quad \text{\hspace{1cm} } m = 10n
\end{align*}
\]  \hspace{1cm} (4.10)
where $n$ is the path loss exponent. The values of $PL_0$ and $n$ depend on the environment and they are usually determined through statistical analysis of path loss data measurements. Table 4.1 gives typical values of $n$ for different propagation environment.

**Table 4.1**: Path loss exponent for different environments [35]

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path loss exponent ($n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7-3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3-5</td>
</tr>
<tr>
<td>In building line of sight</td>
<td>1.6-1.8</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>4-6</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>2-3</td>
</tr>
</tbody>
</table>

Equation (4.9) expressed the average large scale path loss at a given distance ($d$). Graphically, $PL$ is a linear function of ($d$) in logarithmic domain.

**Log Normal Shadowing**

When the actual path loss data are plotted, they show variations about the median path loss given by the model in (4.9). The variations are introduced by log normal shadowing which occurs due the fact that different locations at the same distance from the transmitter might have different environment and therefore the path loss value is different. The $PL(d)$ can be considered as a random variable that is normally distributed in log-domain [35] and it is given as:
where $X_\sigma$ is a log normally distributed random variable that describes the shadowing effects and it can be expressed as:

$$X_\sigma \sim \mathcal{N}(0, \sigma)$$

The operator expressed by (~) means that $X_\sigma$ is a zero mean Gaussian distributed random variable with a standard deviation of $\sigma$. As the model becomes more accurate, the standard deviation $\sigma$ of the unexplained portion ($X_\sigma$) of path loss becomes smaller. Similar to the path loss exponent $n$, $\sigma$ is environmentally dependent. Table 4.2 shows some typical values of $X_\sigma$ for different environments.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Standard deviation ($\sigma$) in dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rural</td>
<td>5-7</td>
</tr>
<tr>
<td>Suburban</td>
<td>6-8</td>
</tr>
<tr>
<td>Urban</td>
<td>8-10</td>
</tr>
<tr>
<td>Dense urban</td>
<td>8-12</td>
</tr>
</tbody>
</table>

### 4.3.3.2 Lee Model

Lee model is one of the most popular and widely used path loss models. It is known for its simplicity along with its reasonable prediction accuracy [40]. Lee model was initially derived for frequencies around 900 MHz. Later on, the model
was extended to frequencies up to 2 GHz [40]. The path loss form of the model is provided relative to reference conditions and is given as [41]:

\[ PL_{Lee} = PL_0 + m \log\left( \frac{d}{d_0} \right) - 15 \log\left( \frac{h_t}{h_{tref}} \right) - 10 \log\left( \frac{h_r}{h_{rref}} \right) \]  

(4.12)

where:

- \( PL_0 \) - Path loss at reference distance (\( d_0 \)) in [dB]
- \( m \) - Slope in [dB/decade]
- \( d \) - Transmitter-receiver separation in [km]
- \( d_0 \) - Reference distance (1.609 km)
- \( h_t \) - Transmitter antenna height in [m]
- \( h_{tref} \) - Reference transmitter antenna height (30.48 m)
- \( h_r \) - Receiver antenna height in [m]
- \( h_{rref} \) - Reference receiver antenna height (3.048 m)

The intercept (\( PL_0 \)) and the slope (\( m \)) for different environments at 900 MHz are provided in Table 4.3.

<table>
<thead>
<tr>
<th>Environment</th>
<th>( PL_0 ) @ ( f_0=900 \text{ MHz} )</th>
<th>( PL_0 ) [dB]</th>
<th>( m ) [dB/decade]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open area</td>
<td>95</td>
<td>43.5</td>
<td></td>
</tr>
<tr>
<td>Suburban</td>
<td>107.7</td>
<td>38.4</td>
<td></td>
</tr>
<tr>
<td>Urban (Philadelphia)</td>
<td>116</td>
<td>36.8</td>
<td></td>
</tr>
<tr>
<td>Urban (Newark)</td>
<td>110</td>
<td>43.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Intercept and slope values for different environments
Whereas the slope \( m \) remains the same for frequencies different than \( f_0 \), frequency correction factor for the intercept \( PL_0 \) is given by:

\[
PL_0(f) = PL_0(f_0) + 20 \log\left(\frac{f}{f_0}\right)
\]  

(4.13)

4.3.3.3 **Hata Model**

Hata model is one of the most commonly used propagation models. The mathematical expression of Hata model is based on extensive field measurements done by Okumura in and around Tokyo city [42]. The median path loss in urban areas is given as [43]:

\[
PL_{50,urban}[\text{dB}] = 69.55 + 26.16 \log(f) - 13.82 \log(h_b) - a(h_m) + (44.9 - 6.55 \log(h_b)) \log(d)
\]  

(4.14)

Hata model is valid for the following ranges:

- **Frequency** \( f \): \( 150 \leq f \leq 1500 \) in MHz
- **Effective transmitter antenna height** \( h_b \): \( 30 \leq h_b \leq 200 \) in m
- **Effective receiver antenna height** \( h_m \): \( 1 \leq h_m \leq 10 \) in m
- **Transmitter- Receiver separation** \( d \): \( 1 \leq d \leq 20 \) in Km.

For a small to medium cities, the correction factor of receiver antenna height \( a(h_m) \) is given as:
\[ a(h_m)[\text{dB}] = (1.1 \log(f) - 0.7)h_m - (1.56 \log(f) - 0.8) \quad (4.15) \]

For large cities, it is given as:

\[ a(h_m)[\text{dB}] = \begin{cases} 
8.29(\log(1.54h_m))^2 - 1.1 & \text{for } 150 \leq f \leq 200 \\
3.2(\log(11.75h_m))^2 - 4.97 & \text{for } 200 < f \leq 1500 
\end{cases} \quad (4.16) \]

Default environment for Hata model is urban environment. If the predictions of path loss are done in different environment, corrections need to be applied.

For suburban areas the model is given as:

\[ PL_{50}[\text{dB}] = PL_{50,urban} - 2\left(\log\left(\frac{f}{28}\right)\right)^2 - 5.4 \quad (4.17) \]

For open rural areas the model is given as:

\[ PL_{50}[\text{dB}] = PL_{50,urban} - 4.78(\log(f))^2 + 18.33\log(f) - 40.94 \quad (4.18) \]

**4.3.3.4 COST-231 Model**

It also known as COST-Hata model. The European Co-operative for Scientific and Technical research (EURO-COST) established the COST-231 working committee to introduce COST-231 model which is considered as an extended version of Hata model to be applicable up to 2 GHz. The frequency range for this model is 1500 MHz- 2000 MHz. The model is widely used for predicting the median path loss in mobile wireless systems and its formula is given by [44]:
\[ PL[dB] = A + B \log(d) + C_m - a(h_m) \]  
\[ A = 46.3 + 33.9 \log(f) - 13.82 \log(h_b) \]  
\[ B = 44.9 - 6.55 \log(h_b) \]

where the parameters \( f, h_b, h_m, \) and \( d \) are the same as defined in Hata model, \( a(h_m) \) is defined in equation (4.15), and

\[ C_m[dB] = \begin{cases} 
0, & \text{for medium sized city and suburban areas} \\
3, & \text{for metropolitan centers} 
\end{cases} \]

The COST231 model is restricted to the following range of parameters:

Frequency \((f)\): \( 1500 \leq f \leq 2000 \) in MHz

Effective transmitter antenna height \((h_b)\): \( 30 \leq h_b \leq 200 \) in m

Effective receiver antenna height \((h_m)\): \( 1 \leq h_m \leq 10 \) in m

Transmitter-Receiver separation \((d)\): \( 1 \leq d \leq 20 \) in Km.

4.3.3.5 IEEE 802.16j Channel Model

This model was developed by IEEE relay task group. It is based on SUI (Stanford University Interim) model and was extended in 2007 to cover relay scenarios in IEEE 802.16j WiMAX systems [45]. The SUI model [46] is based on extensive field measurements collected at 1.9 GHz across the United States in 95 macro cells. The model was mainly derived for suburban areas with three most common terrain types, namely A, B and C. Type A describes areas which are hilly
with moderate-to-heavy tree densities, and it is associated the maximum path loss. Type C applies to areas which are mostly flat with light tree densities and which have the minimum path loss. Type B has a moderate path loss and it represents either hilly terrains with light tree densities or mostly flat terrains with modest to heavy tree densities. In 2007, IEEE802.16 Relay Task Group developed the SUI model and introduced the IEEE802.16j model to cover nine categories of path loss for relay systems [15]. The path loss types are given in Table 4.4.

Table 4.4: Path loss types for IEEE802.16j relay system

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>LOS/NLOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>Macro-cell suburban, ART to BRT for hilly terrain with moderate-to-heavy tree densities.</td>
<td>LOS/NLOS</td>
</tr>
<tr>
<td>Type B</td>
<td>Macro-cell suburban, ART to BRT for intermediate path-loss condition</td>
<td>LOS/NLOS</td>
</tr>
<tr>
<td>Type C</td>
<td>Macro-cell suburban, ART to BRT for flat terrain with light tree densities.</td>
<td>LOS/NLOS</td>
</tr>
<tr>
<td>Type D</td>
<td>Macro-cell suburban, ART to ART</td>
<td>LOS</td>
</tr>
<tr>
<td>Type E</td>
<td>Macro-cell, urban, ART to BRT</td>
<td>NLOS</td>
</tr>
<tr>
<td>Type F</td>
<td>Urban or suburban, BRT to BRT</td>
<td>LOS/NLOS</td>
</tr>
<tr>
<td>Type G</td>
<td>Indoor Office</td>
<td>LOS/NLOS</td>
</tr>
<tr>
<td>Type H</td>
<td>Macro-cell, urban, ART to ART</td>
<td>LOS</td>
</tr>
<tr>
<td>Type J</td>
<td>Outdoor to indoor</td>
<td>NLOS</td>
</tr>
</tbody>
</table>

Note: ART (Above Roof Top), BRT (Below Roof Top)
The IEEE802.16j path loss model for types A/B/C is given in [15] and can be expressed as:

\[
PL[dB] = \begin{cases} 
20 \log \left( \frac{4\pi d}{\lambda} \right) + s & \text{for } d \leq d'_0 \\
A + 10\gamma \log \left( \frac{d}{d'_0} \right) + \Delta PL_f + \Delta PL_h + s & \text{for } d > d'_0
\end{cases}
\]  

(4.22)

where

\[
A = 20 \log \left( \frac{4\pi d'_0}{\lambda} \right) 
\]  

(4.23)

\[
d'_0 = d_0 10^{\left( \frac{\Delta PL_f + \Delta PL_h}{10\gamma} \right)} 
\]  

(4.24)

\[
\gamma = a - bh_b + \frac{c}{h_b} 
\]  

(4.25)

\[
\Delta PL_f [dB] = 6 \log \left( \frac{f}{2000} \right) 
\]  

(4.26)

\[
\Delta PL_h [dB] = \begin{cases} 
-10 \log \left( \frac{h_r}{3} \right) & \text{for } h_r \leq 3 \\
-20 \log \left( \frac{h_r}{3} \right) & \text{for } 3 < h_r < 10
\end{cases}
\]  

(4.27)

where

\[
d_0 = 100 \text{ [m]}
\]

\[
\lambda \quad \text{- Wavelength [m]}
\]

\[
\gamma \quad \text{- Path loss exponent}
\]

\[
f \quad \text{- Operating frequency [MHz]}
\]

\[
h_r \quad \text{- Receiver antenna height [m]}
\]

\[
h_b \quad \text{- Base station antenna height [m]}
\]
\( d \) - Transmitter-Receiver separation [m]

\( \Delta PL_f \) - Correction factor for the frequency [dB]

\( \Delta PL_h \) - Correction factor for the receiver antenna height [dB]

\( a, b \) and \( c \) are constants and they depend on the terrain type as provided in Table 4.5.

**Table 4.5: Parameters for the terrain type A/B/C**

<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Terrain A</th>
<th>Terrain B</th>
<th>Terrain C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>4.6</td>
<td>4</td>
<td>3.6</td>
</tr>
<tr>
<td>( b ) [m-1]</td>
<td>0.0075</td>
<td>0.0065</td>
<td>0.005</td>
</tr>
<tr>
<td>( c ) [m]</td>
<td>12.6</td>
<td>17.1</td>
<td>20</td>
</tr>
</tbody>
</table>

The parameter \( s \) in equation (4.22) represents the shadowing effect and it has lognormal distribution. The typical value of the standard deviation of \( s \) for the various categories is listed in Table 4.6.

**Table 4.6: Standard deviation for different categories**

<table>
<thead>
<tr>
<th>Category</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
<th>Type E</th>
<th>Type F</th>
<th>Type G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LOS NLOS</td>
<td>LOS NLOS</td>
</tr>
<tr>
<td>( s ) [dB]</td>
<td>10.6</td>
<td>9.6</td>
<td>8.2</td>
<td>3.4</td>
<td>8.0</td>
<td>2.3</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Restrictions to IEEE802.16j model are:

- \( h_b \) is 10-80 [m]
- $h_r$ is 2-10 [m]
- $d$ is 0.1-8 [km]

### 4.3.3.6 WINNER II Model

This model was developed by IST-WINNER II project [14]. It covers a wide range of propagation scenarios and environments. Path loss model for the different WINNER scenarios have been developed based on measurements conducted within WINNER, as well as results from the open literature. Among these scenarios are the path loss models for fixed relays (i.e., stationary feeders), namely the scenario B5 which it further divided into five sub-scenarios according to the relay location as it illustrated in Table 4.7.

<table>
<thead>
<tr>
<th>Sub-scenario</th>
<th>LOS/NLOS</th>
<th>Transmitter location</th>
<th>Receiver location</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5a</td>
<td>LOS</td>
<td>Above rooftop</td>
<td>Above rooftop</td>
</tr>
<tr>
<td>B5b</td>
<td>LOS</td>
<td>Street level</td>
<td>Street level</td>
</tr>
<tr>
<td>B5c</td>
<td>LOS</td>
<td>Below rooftop</td>
<td>Street level</td>
</tr>
<tr>
<td>B5d</td>
<td>NLOS</td>
<td>Above rooftop</td>
<td>Street level</td>
</tr>
<tr>
<td>B5f</td>
<td>LOS/NLOS</td>
<td>Above rooftop</td>
<td>Below/above rooftop</td>
</tr>
</tbody>
</table>

Based on [14], WINNER B5f sub-scenario is the most appropriate channel model to predict the path loss for the link between the base station (i.e. eNodeB) and relay station (backhaul link). WINNER B5f model takes into account both LOS
and NLOS conditions where the base station antenna height is above the rooftop level and the relay station antenna height is either above or below the rooftop level.

According to [14], the path loss model for various WINNER scenarios are typically given as:

$$PL[\text{dB}] = A \log(d) + B + C \log\left(\frac{f}{5}\right)$$  \hspace{1cm} (4.28)

Where $A=23.5$, $B=57.5$ and $C=23$ for the sub-scenario B5f which is suitable for predicting the path loss in urban areas, and

- $f$ - Frequency of operation [GHz], $2 \text{ GHz} < f < 6 \text{ GHz}$
- $d$ - Base station-Relay station separation [m], $30 \text{ m} < d < 1.5 \text{ km}$

It is important to note that this model was derived for base station antenna height ($h_{BS}=25 \text{ m}$) and relay station antenna height ($h_{RS}=15 \text{ m}$).

### 4.3.3.7 3GPP models

3rd Generation Partnership Project suggested some propagation models for predicting path loss in various environments [8, 47]. Among them were models dedicated to BS-RS links. Those models distinguish between two scenarios, namely LOS and NLOS. The models expressions are given by:

$$PL_{LOS}[\text{dB}] = 100.7 + 23.5 \log(d)$$  \hspace{1cm} (4.29)
and

\[ PL_{NLOS}[\text{dB}] = 125.2 + 36.3 \log(d) \quad (4.30) \]

Where \( d \) in [km] is the distance between the base station and the relay station. While equation (4.29) is used when the direct component LOS is dominant which occurs when there are no obstacles between the transmitter and the receiver, equation (4.30) is used otherwise (NLOS scenario). Path loss models in equations (4.29) and (4.30) were derived under the following conditions:

- \( f \) - Operating frequency [2 GHz]
- \( h_{bs} \) - Base station antenna height [30 m]
- \( h_{rs} \) - Relay station antenna height [5 m]

And the log-normal shadowing standard deviation was assumed to be 6 dB.

The path loss expressed in (4.29) and (4.30) are plotted in Figure 4.3. The figure shows significant difference in path loss value between LOS and NLOS conditions. For example, at 200 m distance, the path loss in the case of LOS is about 85 dB whereas the path loss in the case of NLOS is 100 dB, i.e. the path loss in LOS condition is smaller by 15 dB. This difference increases with increasing distance between base station and relay station. The main difference between the two path loss curves in Figure 4.3 is in the vertical interceptions and the slope.
Figure 4.3: Path loss vs. distance of 3GPP model for LOS and NLOS

In general, when relay station is close to base station, there is a high probability that LOS is dominant. On the contrary, for far distances, NLOS condition is more likely. The LOS probability is a function of different environmental factors, including clutter, street canyons, and distance. The LOS probability for different environments is given in Table 4.8.

The dependency of LOS on the distance for various environments is shown in Figure 4.4.
Table 4.8: LOS probability for different environments [8]

<table>
<thead>
<tr>
<th>Environment</th>
<th>LOS probability function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>$p(d) = \min\left(0.018 \frac{d}{d}, 1\right)(1 - e^{-\frac{d}{0.072}}) + e^{-\frac{d}{0.072}}$</td>
</tr>
<tr>
<td>Suburban</td>
<td>$p(d) = e^{-(d-0.01)/0.23}$</td>
</tr>
<tr>
<td>Suburban/Rural</td>
<td>$p(d) = e^{-(d-0.01)/1.15}$</td>
</tr>
</tbody>
</table>

Figure 4.4: LOS probability as a function of distance for different environments

As Table 4.8 and Figure 4.4 show, LOS condition is more dominant in rural and suburban areas than urban ones. For example, at 200 m distance, the LOS probability is about 15%, 44%, and 85% for urban, suburban and rural environment, respectively.
Taking LOS probability into consideration, the combined path loss is given as:

\[ PL(d) = p(d).PL_{LOS} + [1 - p(d)].PL_{NLOS} \]  

Figure 4.5, 4.6 and 4.7 describe the behavior of path loss as a function of distance in LOS, NLOS and combined LOS/NLOS conditions for urban, suburban and rural environments, respectively.

\[ \text{Figure 4.5: Path loss of 3GPP model considering LOS probability for urban environment} \]
Figure 4.6: Path loss of 3GPP model considering LOS probability for suburban environment

Figure 4.7: Path loss of 3GPP model considering LOS probability for suburban/rural environment
For urban areas, as presented in Figure 4.5, the path loss follows the LOS curve when relay station is close to base station (for $d$ smaller than 40 m). On the other hand, as relay station further away from base station (for $d$ greater than 400 m), the path loss follows the NLOS curve. Roughly in the range between 30 m and 300 m, the path loss is considered as a combination between LOS and NLOS conditions. In the cases of suburban areas (Figure 4.6) and suburban/rural areas (Figure 4.7), the combined path loss is pronounced roughly in the range between 50 m and 700 m, and between 100 m and 4 km, respectively. Note that the combined path loss is only in average sense. However, in practical scenarios, relay station can either be in LOS or NLOS with base station, not both.

### 4.3.3.8 New relaying model

This model was developed based on measurements carried out in a typical urban medium city of Belfort, France [21]. The model was proposed to predict path loss encountered on the link between the base station and relay station. The model was specifically derived for LTE-Advanced relaying systems operating in urban environments. The proposed model takes into account the impact of relay antenna height and it is given by:

$$PL[dB] = 34 \log(d) + 5 + 26 \log(20 - h_{RS})$$  \hspace{1cm} (4.32)

where $d$ in [m] is distance between base station and relay station, $h_{RS}$ in [m] is the relay station antenna height. The model is valid for predicting path loss in the
relay link operates in 2.1 GHz band in NLOS conditions and with \( d \) ranges from 20-1000 m. The relay height is limited up to 15 m and the error standard deviations are in the range of 7-8 dB [21].

Each individual propagation model has its own set of assumptions and is restricted to a specific range of parameters under which it was derived. When a propagation model is used to predict path loss outside of the specified parameter range, its validity becomes questionable. Table 4.9 summarizes the range of parameters under which the previously mentioned propagation models were derived.

**Table 4.9: Summary of path loss models and their restrictions**

<table>
<thead>
<tr>
<th>Model</th>
<th>Receiver antenna height ( (h_r) ) in [m]</th>
<th>Transmitter antenna height ( (h_t) ) in [m]</th>
<th>Distance ( (d) ) in [km]</th>
<th>Operating frequency ( (f) ) in [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hata</td>
<td>1-10</td>
<td>30-200</td>
<td>1-20</td>
<td>150-1500</td>
</tr>
<tr>
<td>COST-231</td>
<td>1-10</td>
<td>30-200</td>
<td>1-20</td>
<td>1500-2000</td>
</tr>
<tr>
<td>IEEE 802.16j</td>
<td>1-10</td>
<td>10-80</td>
<td>0.1-8</td>
<td>1900-11000</td>
</tr>
<tr>
<td>WINNER II</td>
<td>15</td>
<td>25</td>
<td>0.03-1.5</td>
<td>2000-6000</td>
</tr>
<tr>
<td>3GPP</td>
<td>5</td>
<td>30</td>
<td>NS</td>
<td>2000</td>
</tr>
<tr>
<td>Lee</td>
<td>1-15</td>
<td>20-100</td>
<td>up to 20</td>
<td>850-2000</td>
</tr>
<tr>
<td>Relay model [21]</td>
<td>4-15</td>
<td>22</td>
<td>0.02-1</td>
<td>2100</td>
</tr>
</tbody>
</table>
Chapter 5: Development of Propagation Model for Relay Stations

5.1 Measurement Environment

RF propagation models are geographically dependent. Environment type is one of the geographical variables that has a major impact on the propagation model applicability. In general, the environments in which the propagation model is going to be used, are classified into three main categories: urban, suburban and rural. It is noteworthy to point out that the classification of environment is different from one continent to another. For instance, Hata-Okummura model which was developed in Japan, needs to be modified when it is used in the United States to get satisfactory results. That is because the model was derived in Japanese environment which is definitely different from the US environment in terms of area classification, terrain, constructions etc.

The measurements in this work were conducted in an environment that may be classified as suburban. Furthermore, since most of the US cities may be considered as suburban area, the hope is that the developed models are going to be applicable to similar kinds of environments across the country. The proposed approach is to develop path loss models for relaying systems by conducting
comprehensive measurements and explaining the behavior of the path loss as a function of distance and relay station antenna height. Since the model is based on field measurements, it is statistical in nature and it falls into the category of other statistical macroscopic propagation models that have been covered in chapter 4.

5.2 PCS Frequencies

The electromagnetic spectrum covers a wide range of frequencies. However, practical bands used in radio communication range from 3 kHz to 300 GHz as it is shown in Table 5.1. The corresponding wavelengths in free space vary from 100 km to 1 mm.

<table>
<thead>
<tr>
<th>Category</th>
<th>Acronym</th>
<th>Frequency</th>
<th>Wavelength (λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Low Frequency</td>
<td>ELF</td>
<td>&lt; 3 kHz</td>
<td>&gt; 100 km</td>
</tr>
<tr>
<td>Very Low Frequency</td>
<td>VLF</td>
<td>3 kHz-30 kHz</td>
<td>10 km-100 km</td>
</tr>
<tr>
<td>Low Frequency</td>
<td>LF</td>
<td>30 kHz-300 kHz</td>
<td>1 km-10 km</td>
</tr>
<tr>
<td>Medium Frequency</td>
<td>MF</td>
<td>300kHz-3 MHz</td>
<td>100 m-1 km</td>
</tr>
<tr>
<td>High Frequency</td>
<td>HF</td>
<td>3 MHz-30 MHz</td>
<td>10 m-100 m</td>
</tr>
<tr>
<td>Very High Frequency</td>
<td>VHF</td>
<td>30 MHz-300 MHz</td>
<td>1 m-10 m</td>
</tr>
<tr>
<td>Ultra High Frequency</td>
<td>UHF</td>
<td>300 MHz-3 GHz</td>
<td>10 cm-1 m</td>
</tr>
<tr>
<td>Super High Frequency</td>
<td>SHF</td>
<td>3 GHz-30 GHz</td>
<td>1 cm-10 cm</td>
</tr>
<tr>
<td>Extra High Frequency</td>
<td>XHF</td>
<td>30 GHz-300 GHz</td>
<td>1 mm-1 cm</td>
</tr>
</tbody>
</table>
Most mobile radio communication applications are located in the frequency bands from 30 MHz to 3 GHz (VHF/UHF bands). In these bands the corresponding wavelength runs from 10 cm to 10 m. Therefore, VHF/UHF are the most suitable bands for wireless communications due to the fact that the antenna size needs to be comparable to the wavelength. More specifically, Personal Communication Service (PCS), which describes any of many types of wireless voice and/or data communication systems, are provided in the 1850-1990 MHz band. This band is commonly referred to as 1900 MHz band.

The measurements in this work were taken place in 1900 MHz band and therefore the model is going to be strictly applicable for that frequency. Nevertheless, other models were developed for one frequency and then they have been shown that with some minor modifications can be extended to other frequency ranges.

5.3 Developing the Link between Relay Model and Existing Models

There are many propagation models that are already coded, and they are part of software packages that are used for development. Well-known examples of these models are Hata model, COST 231-Hata model, Lee model etc. To this end, an introduction of a new model is much easier if it relies on the ones that already exist. One of the goals of this research is to examine the difference between
measurements and one or more of the standard models and then derive correction factors so these models can be used in relaying scenarios. In other words, a link to the already coded standard models can be established by some modifications on existing software. Consequently, software implementation of the developed models will be straightforward without need to implement new codes to introduce new models.

5.4 Mathematical Modeling

The approach here is to develop an empirical propagation path loss model that explains the observed data. In the first order approximation, the predicted path loss in [dB] at any given distance \(d\) with respect to a reference distance \(d_0\) may be described using the log-distance path loss model as it was given by equation (4.9) in Chapter 4. Recalling the equation:

\[
PL(d) = PL_0 + m \log\left(\frac{d}{d_0}\right)
\]  

(5.1)

The parameters of the model, \(m\) the slope and \(PL(d_0)\) the median path loss at the \(d_0\), are determined through statistical analysis of measurements collected across various system configurations. The optimization of the path loss model given in (5.1) can be achieved by first comparing measured and predicted values of path loss, and then using the MMSE (Minimum Mean Square Error) method to
minimize the difference between predictions and measurements. Considering a measurement process, then for every measurement point one can write:

\[ PL_{pi} = PL_0 + m \log \left( \frac{d_i}{d_0} \right) \]  \hspace{1cm} (5.2)

and

\[ PL_{mi} = ERP - P_{ri} \]  \hspace{1cm} (5.3)

where

- \( PL_{pi} \): Predicted path loss for the \( i^{th} \) point
- \( PL_{mi} \): Measured path loss for the \( i^{th} \) point
- \( ERP \): Effective Radiated Power
- \( P_{ri} \): Received power at point \( i \)

The difference between measured and predicted path loss value for the \( i^{th} \) point is expressed as:

\[ \delta_i = PL_{mi} - PL_{pi} \]  \hspace{1cm} (5.4)

where \( \delta_i \) is the prediction error for the \( i^{th} \) point and \( i=1, 2, \ldots N \).

Substituting (5.2) into (5.4), one may write:
\[ \delta_i = P_{L_{ml}} - P_{L_0} - m \log \left( \frac{d_i}{d_0} \right) \]  

(5.5)

Taking all measurement points \((N)\) into account, the expression in (5.5) may be written in a matrix format as:

\[
\begin{bmatrix}
\delta_1 \\
\delta_2 \\
\vdots \\
\delta_N
\end{bmatrix} =
\begin{bmatrix}
P_{L_{m1}} \\
P_{L_{m2}} \\
\vdots \\
P_{L_{mN}}
\end{bmatrix} - P_{L_0}
\begin{bmatrix}
1 \\
1 \\
\vdots \\
1
\end{bmatrix} - m
\begin{bmatrix}
\log \left( \frac{d_1}{d_0} \right) \\
\log \left( \frac{d_2}{d_0} \right) \\
\vdots \\
\log \left( \frac{d_N}{d_0} \right)
\end{bmatrix}
\]  

(5.6)

The objective here is to determine the optimum values of \(P_{L_0}\) and \(m\) that minimize the norm of the prediction error vector \(\delta\). In other words, the cost function given by:

\[ J(\delta) = \delta^T \delta = \sum_{i=1}^{N} \delta_i^2 \]  

(5.7)

needs to be minimized.

By substituting (5.6) into (5.7), one may write:
\[
J(\delta) = \sum_{i=1}^{N} \begin{pmatrix} PL_{m1} \\ PL_{m2} \\ \vdots \\ PL_{mN} \end{pmatrix} - PL_0 \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} - m \begin{pmatrix} \log \left( \frac{d_1}{d_0} \right) \\ \log \left( \frac{d_2}{d_0} \right) \\ \vdots \\ \log \left( \frac{d_N}{d_0} \right) \end{pmatrix}^2
\]

(5.8)

To get the minimal sum of the error squared, the partial derivative of equation (5.8) with respect to \(PL_0\) and \(m\) needs to be zero.

First, considering the partial derivative of (5.8) with respect to \(PL_0\), one gets:

\[
\frac{\partial J(\delta)}{\partial PL_0} = 2 \sum_{i=1}^{N} \begin{pmatrix} PL_{m1} \\ PL_{m2} \\ \vdots \\ PL_{mN} \end{pmatrix} - PL_0 \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} - m \begin{pmatrix} \log \left( \frac{d_1}{d_0} \right) \\ \log \left( \frac{d_2}{d_0} \right) \\ \vdots \\ \log \left( \frac{d_N}{d_0} \right) \end{pmatrix} = 0
\]

(5.9)

Simplifying and rearranging (5.9), one may write:

\[
\sum_{i=1}^{N} PL_{mi} - N \times PL_0 = m \sum_{i=1}^{N} \log \left( \frac{d_i}{d_0} \right)
\]

(5.10)

Now, considering the partial derivative of (5.8) with respect to \(m\), one gets:
\[
\frac{\partial J(\delta)}{\partial m} = 2 \sum_{i=1}^{N} \begin{bmatrix} PL_{m1} \\ \vdots \\ PL_{mN} \end{bmatrix} - PL_0 \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} - m \begin{bmatrix} \log \left( \frac{d_1}{d_0} \right) \\ \vdots \\ \log \left( \frac{d_N}{d_0} \right) \end{bmatrix} \begin{bmatrix} \log \left( \frac{d_1}{d_0} \right) \\ \vdots \\ \log \left( \frac{d_N}{d_0} \right) \end{bmatrix} = 0 \quad (5.11)
\]

Simplifying and rearranging (5.11), one may write:

\[
\sum_{i=1}^{N} PL_{mi} \log \left( \frac{d_i}{d_0} \right) - PL_0 \sum_{i=1}^{N} \log \left( \frac{d_i}{d_0} \right) = m \sum_{i=1}^{N} \log^2 \left( \frac{d_i}{d_0} \right) \quad (5.12)
\]

Define:

\[
A = \sum_{i=1}^{N} \log \left( \frac{d_i}{d_0} \right) \quad (5.13)
\]

\[
B = \sum_{i=1}^{N} \log^2 \left( \frac{d_i}{d_0} \right) \quad (5.14)
\]

\[
C = \sum_{i=1}^{N} PL_{mi} \quad (5.15)
\]

\[
D = \sum_{i=1}^{N} PL_{mi} \log \left( \frac{d_i}{d_0} \right) \quad (5.16)
\]

Substituting (5.13) to (5.16) into (5.10) and (5.12), one gets:
\[ C - N \ast PL_0 = mA \quad (5.17) \]

\[ D - A \ast PL_0 = mB \quad (5.18) \]

By solving (5.17) and (5.18), one obtains the optimum values of \( PL_0 \) and \( m \), and they may be given as:

\[ PL_0 = \frac{BC - AD}{BN - A^2} \quad (5.19) \]

\[ m = \frac{DN - AC}{BN - A^2} \quad (5.20) \]

An optimized statistical model for predicting path loss can now be obtained by substituting the optimum values of \( PL_0 \) and \( m \) into the path loss model form given by (5.1).
Chapter 6: Measurement System and Procedure

6.1 Equipment Description

The measurement system consists of a PCS transmitter, transmit antenna, receiver, receive antenna, GPS (Global Positioning System) and a laptop with installed measurement software from Grayson wireless.

6.1.1 Transmitter

The Berkeley Varitronics Systems Transmitter consists of a continuous wave (CW) generator and power amplifier. This transmitter can be used for measuring PCS band signal propagation. It covers the frequency range 1.85 to 2.1 GHz. The transmit power is up to 20 Watt or 43 dBm. The transmitter has a control knob which is used for adjusting both frequency and power to the desired level. It also has an LCD screen for displaying frequency, RF power and operating status. Figure 6.1 shows the transmitter used in this work.
6.1.2 Transmit antenna

The base station antenna which was used in the measurements is presented in Figure 6.2. This antenna is used to transmit signals in the frequency range from 1850 MHz to 1990 MHz.

Table 6.1 gives the technical specifications of the transmit antenna.
Table 6.1: Transmit antenna technical specifications

<table>
<thead>
<tr>
<th>Frequency Range [MHz]</th>
<th>Type</th>
<th>Gain [dBi]</th>
<th>Polarization</th>
<th>Length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1850-1990</td>
<td>Omni</td>
<td>6</td>
<td>Vertical</td>
<td>90</td>
</tr>
</tbody>
</table>

6.1.3 Antenna Pattern

The antenna pattern describes how the antenna radiates energy into space. In general, the patterns are specified using two principal patterns: elevation pattern and azimuth pattern. Whereas the elevation pattern describes the pattern in the vertical plane, the azimuth pattern refers to the pattern in the horizontal plane. The patterns are used to determine the antenna gain in a given direction. Based on their gain pattern the antennas may be classified as: isotropic, directional and omni-directional. Isotropic antenna radiates energy equally in all directions and it has a uniform gain. These kind of antennas would have a spherical radiation pattern. Directional antenna radiates energy more effectively in one or more directions than in others. Typically, these type of antennas have one main lobe and several minor lobes. Omni-directional antenna radiates energy uniformly in a certain plane (circular in shape) with a directional pattern in any other orthogonal plane.

The transmit antenna used in this work is an omni-directional antenna in the horizontal plane, that is it has a uniform pattern in azimuth plane. This means also that the transmit antenna has a uniform gain in azimuth (horizontal) direction with
directional gain in the elevation (vertical) direction. Figure 6.3 illustrates a plane cut in a polar coordinates of the azimuth pattern of the antenna used in this work. The actual antenna gain in the azimuth direction varies between about 6 to 7 dB. This variation may be neglected and therefore the gain in the azimuth direction is averaged and it is equal to 6.5 dB.

**Figure 6.3:** Azimuth antenna pattern in polar coordinates

While the antenna gain is approximately constant in the azimuth plane, it changes significantly as a function of the elevation. This means that the antenna gain is a function of the elevation angle between the transmitter and receiver.
Figure 6.4 shows a plane cut of the antenna elevation pattern. The maximum antenna gain, which occurs in this case at the elevation angle of zero degree, is 6.5 dB. However, for illustrative proposes, the antenna gain is shifted by 30 dB. The antenna pattern data are provided in the appendix. As can be seen from the appendix, there are two sets of data for antenna gain in elevation direction are provided. The average of the two sets was considered as the antenna gain in elevation direction in this work.

Figure 6.4: Elevation antenna pattern in polar coordinates
It is sometimes useful to plot the antenna pattern in Cartesian coordinates, especially when there are several minor lobes (as for the antenna used in this work), and where the levels of these minor lobes are of special importance. Figure 6.5 re-illustrates the antenna elevation pattern in the Cartesian coordinates. As seen, the main lobe of the antenna pattern is between elevation angles ($\theta$) equal to -11 to 11 degrees. However, from practical implementation prospective, the only interesting part of this lobe is the one that is associated with the negative values of $\theta$.

**Figure 6.5:** Elevation antenna pattern in Cartesian coordinates
As can be seen from Figure 6.5, the antenna gain drops from its maximum (6.5 dB) for $\theta=0$ to about -13 dB for $\theta=-11$ degrees. For the considered transmit antenna in this work, the gain has positive values for $\theta$ ranges between 0 and -7 degrees as it is presented in Table 6.2.

<table>
<thead>
<tr>
<th>$\theta^\circ$</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
<th>-4</th>
<th>-5</th>
<th>-6</th>
<th>-7</th>
<th>-8</th>
<th>-9</th>
<th>-10</th>
<th>-11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain [dB]</td>
<td>6.5</td>
<td>6.5</td>
<td>6.4</td>
<td>6</td>
<td>5.7</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>-0.4</td>
<td>-3.7</td>
<td>-7.9</td>
<td>-13.5</td>
</tr>
</tbody>
</table>

To make sure that antenna pattern effects are considered properly, only antenna gain values for which $\theta$ is between 0 and -11 degrees (main lobe) are considered. This means that only measurement locations for which the elevation angle between relay station and base station is smaller than 11 degrees will be taken into account.

### 6.1.4 Receiver

Figure 6.6 shows the Grayson Wireless Measurement System receiver which was used for measuring the received signal level. The receiver is provided with four inputs. Each input can be connected to a separate antenna. Thus, the receiver has the ability to process four signals simultaneously. It covers two frequency bands, i.e. PCS band and cellular band. Whereas input 1 and input 2 are used for receiving
PCS band signals, input 3 and input 4 are allocated for cellular band signals. The corresponding channel bandwidth is 12 kHz and 30 kHz, respectively.

![Figure 6.6: Receiver](image)

The frequency range for PCS and cellular bands are 1850-1990 MHz and 824-894 MHz, respectively. Table 6.3 summarizes these values.

<table>
<thead>
<tr>
<th>Antenna Port</th>
<th>Receiver Type</th>
<th>Frequency range</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GMR 203N (PCS)</td>
<td>1850-1990 MHz</td>
<td>12 kHz</td>
</tr>
<tr>
<td>2</td>
<td>GMR 203N (PCS)</td>
<td>1850-1990 MHz</td>
<td>12 kHz</td>
</tr>
<tr>
<td>3</td>
<td>GMR 200 (Cellular)</td>
<td>824-894 MHz</td>
<td>30 kHz</td>
</tr>
<tr>
<td>4</td>
<td>GMR 200 (Cellular)</td>
<td>824-894 MHz</td>
<td>30 kHz</td>
</tr>
</tbody>
</table>
The receiver is provided with a GPS to determine the coordinates of the point of interest. Furthermore, the receiver can be connected to a laptop with installed measurement software to process and analyze the measurements (will be described in section 6.1.6).

6.1.5 **Receive antenna**

In this proposal work two receive antennas were used. While the first one was used to represent the mobile station at certain height level, the other one was installed at a higher level to simulate the relay station. The two antennas are almost identical. Both of them have omni-directional pattern and cover the entire PCS frequency band. The technical specifications for both antennas are summarized in Table 6.4. Figure 6.7 shows one of the antennas that was used in this work.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile</td>
<td>1850-1990</td>
<td>2.5</td>
<td>Omni</td>
<td>9</td>
<td>3.5</td>
<td>12</td>
</tr>
<tr>
<td>Relay</td>
<td>1850-1990</td>
<td>5</td>
<td>Omni</td>
<td>8.5</td>
<td>2.4</td>
<td>15</td>
</tr>
</tbody>
</table>

**Table 6.4:** Technical specifications of receive antennas
6.1.6 Software

The software that was used to establish the measurements in this work is called Wireless Measurement System (WMS). It is installed on a laptop and it consists of a Cellscope and Spectrum tracker software. The software is used to measure the level of the received signals and map their values on the spectrum tracker screen along with corresponding frequencies. Much like a spectrum analyzer, the spectrum tracker maps the frequency on the x-axis [in MHz] and the signal strength on the y-axis [in dBm]. The spectrum tracker can process up to four receivers simultaneously. The display reports real time measurements from the receiver selected in the spectrum tracker submenu. The signal strengths and their corresponding frequencies can be displayed either numerically or graphically. The maximum and minimum graphical signal strengths are -45 dBm and -130 dBm, respectively. Moreover, the software produces a log file for every recording session. The log file provides a complete reported listing of all of the real time
activity. This list includes time, date, frequency, received signal level and receiver coordinates. Figure 6.8 presents a snapshot of the main menu of the software along with an example of power measurements at some PCS frequencies. Additionally, it shows a numerical display of received signal level for some frequencies. Figure 6.9 gives a graphical illustration of RSL for some other frequencies.

![Image of software interface](image)

**Figure 6.8**: Power measurements: numerical display
Figure 6.9: Power measurements: graphical display

6.2 Receiver Noise Floor and Noise Figure

The noise power at the input of a receiver can be given as

\[ P_N = kTB \]  \hspace{1cm} (6.1)

where

\( k \): Boltzmann’s constant = \( 1.379 \times 10^{-23} \) [W/HzK]

\( T \): Absolute temperature in Kelvin [K]

\( B \): Receiver bandwidth in Hertz [Hz]
Using Formula (6.1) and considering Table 6.3 for the antenna port 1 \((B=12 \text{ kHz})\), one can obtain the input noise floor at room temperature \((295 \text{ K})\) as following:

\[
kT = 295 \times 1.379 \times 10^{-23} = 4.07 \times 10^{-21} \text{ W/Hz} = 4.07 \times 10^{-18} \text{ mW/Hz} \quad (6.2)
\]

\[
P_N = kT B = 4.07 \times 10^{-18} \times 12 \times 10^3 = 4.884 \times 10^{-14} \text{ mW} = -133.11 \text{ dBm}. \quad (6.3)
\]

At the output of the receiver the noise power increases as a result of the active electronic components. This augmentation is called noise figure \((F)\). It is simply the ratio of the \(SNR_{input}\) to the \(SNR_{output}\). This relation can be expressed in decibel as:

\[
F[\text{dB}] = SNR_{input}[\text{dB}] - SNR_{output}[\text{dB}] \quad (6.4)
\]

Therefore, the receiver noise floor \((NF)\) can be calculated as:

\[
NF[\text{dBm}] = kTB[\text{dBm}] + F[\text{dB}] \quad (6.5)
\]

Taking into account that our receiver has a noise figure, \(F\) about 2 dB, it is possible now to determine the noise floor of the receiver. Considering the result from (6.3) and substituting it in (6.5), one gets that \(NF = -131.11 \text{ dBm}\). This means, if the average received signal level \((RSL_{avg})\) is around this value, then it is likely that what is being received is nothing but noise.
6.3 Spectrum Clearing

Before conducting the experimental survey, one has to make sure that the operating frequency used for the path loss measurements is not occupied by any other applications. In other words, the operating frequency has to be free from any sources of radiation. Otherwise, the measurements will be corrupted with the outside interference. This process is called spectrum clearing. In order to achieve this task, monitoring process for the frequency of interest needs to be established. The measurement system that has been used for this purpose is illustrated in Figure 6.10, and it consists of the receiver, antenna and laptop with preinstalled software to measure the received signal level.

\[
\text{Figure 6.10: Spectrum clearing measurement system}
\]
The antenna was connected to the port 1 to monitor the desired operating frequency, which is 1925 MHz in this work. The approach here is to ensure that this frequency is not in use. The monitoring process took place in the Wireless Center of Excellence (WiCE) lab at Florida Institute of Technology and lasted for 24 hours. The received signal values were recorded as a log file then were transferred through a macrocode to be presented in a much easier format to work with.

More than 788,200 measurements were recorded in this test. The signal strength measurements for the 24 hours test are described by the histogram in Figure 6.11. It is noticeable that the frequency 1925 MHz is not occupied by any application. This is because the average measured signal level was around -128 dBm, for about 50% of the time, which is just noise. Taking into account that the antenna gain (2.5 dB), and comparing this result to the \( NF \) value (-131.11 dBm) obtained in section 6.2, one finds an excellent match between the theoretical and the measured value of \( NF \). The figure also shows the normal distribution of the noise around its mean value with a standard deviation less than 2 dB.
Figure 6.11: Signal strength measurements at frequency 1925 MHz for 24 hours

6.4 Procedure

Measurements were conducted by using the equipment described in the previous sections. The experimental data were collected in outdoor environment during the daytime. The measurements are conducted over a period of couple of weeks, with essentially no changes in weather pattern and vegetation. The measurements conducted for this work are collected in a typical US suburban environment of Melbourne, FL, USA. Most houses in the selected area were single to double stories and their heights were about 4 to 9 meters. In general, most of the buildings are made of wooden structures with exception of few buildings that are
made of combined materials; concrete for frame or body and timber or plastered bricks for walls, glass for windows, concrete for floors. Few buildings have flat roofs while most of one story houses and two stories residential apartments have pitched roofs. The terrain in general is flat with moderate tree densities. Trees height is up to 13 m.

In this measurement campaign, both the base station transmitter and receiver were fixed. At transmission side, the antenna was an omni-directional type with 6 dBi gain and vertical polarization. The base station antenna was attached to a mast and mounted on the top of multi-story building (Crawford Building at Florid Institute of Technology) as it is shown in Figure 6.12. Therefore, the actual height of the transmitting antenna is the summation of the height of the building, height of the mast and half height of the antenna itself. The antenna was then connected to the transmitter that is generating a continuous wave (CW) signal (un-modulated single tone carrier). The measurements are collected in 1900MHz band which is one of the principal bands for the deployment of the LTE and LTE-Advanced. The transmitted power was set up at 43 dBm.
At the reception side, data collection process are divided into two campaigns. First measurement campaign was performed to collect the data for two levels of receive antenna height, namely 1.7 and 4 meters. Those heights were chosen to represent the mobile station and relay station, respectively as it is shown in Figure 6.13. The measurement equipment were installed on a cart that can be moved. Two omni-directional antennas were attached to two plastic masts. Both antennas were connected to the receiver to measure the received signal strength at the mobile station and relay station.
The second measurement campaign was conducted using four different relay heights ranging from 4 to 16 meters with 4 meter step. The considered heights are typical where one would find relay deployment in various scenarios. In this measurement campaign, the receiver was placed in a boom-lift as shown in Figure 6.14 and moved between locations.

Figure 6.13: Illustration of the mobile and relay stations
At each measurement point, a GPS was used to determine the coordinates of the receiver. Consequently, the distance from the base station to the receiver can be calculated. The location of the measurement points in the second campaign is presented in Figure 6.15.

The parameters associated with the measurements are provided in Table 6.5
**Figure 6.15**: Map of the area where the measurements were conducted. Transmitter location is – Latitude: 28.064° N, Longitude: 80.624° W

**Table 6.5**: Parameters associated with the measurement campaign

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>1925 MHz</td>
</tr>
<tr>
<td><strong>Transmitter</strong></td>
<td></td>
</tr>
<tr>
<td>Antenna height</td>
<td>25.5 m</td>
</tr>
<tr>
<td>Transmitting power</td>
<td>43 dBm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>6 dBi</td>
</tr>
<tr>
<td>Cable and connector losses</td>
<td>0.5 dB</td>
</tr>
<tr>
<td><strong>Mobile Station</strong></td>
<td></td>
</tr>
<tr>
<td>Antenna height</td>
<td>1.7 m</td>
</tr>
<tr>
<td>Antenna gain including cable and connector losses</td>
<td>11.7 dBi</td>
</tr>
<tr>
<td><strong>Relay Station</strong></td>
<td></td>
</tr>
<tr>
<td>Antenna height</td>
<td>4, 8, 12, 16m</td>
</tr>
<tr>
<td>Antenna gain including cable and connector losses</td>
<td>5 dBi</td>
</tr>
</tbody>
</table>
All parameters related to measurements including received signal level, location of the receiver, date and time were recorded using a laptop with the software described in section (6.1.6). The measurement system is shown in Figure 6.16.

**Figure 6.16: Measurement system**

Measurements were conducted at different locations on roads in coverage area within a region from 100 m to about 4 km from the base station. Whereas for the first campaign measurements were taken at 155 different locations, 100 of path loss measurement locations are examined for each relay antenna height in the second campaign. For each examined antenna height, data were recorded at interval of 20 ms for about 3-5 minutes. For each measurement location several hundred readings are averaged in time domain so that the fast-fading component of the
signal is smoothed out. Then, the path loss at each location for the different receiver antenna heights was calculated by using the averaged measured received signal level.
Chapter 7: Path Loss Measurements for Relay Stations

The main objective of the research described in this chapter is to develop statistical path loss models for outdoor relaying systems [48, 49]. The path loss models are derived on a basis of an extensive measurement campaign conducted in 1900 MHz frequency band. The results obtained from the measurements are presented and discussed in this chapter. Path loss measurements are compared with path losses predicted using the model given in (5.1). Additionally, the impact of the relay station antenna height is studied and included in the path loss modeling. An antenna height correction factor is also derived and included in the modeling. Finally, a relationship between the intercept, slope of the model and the relay antenna height is derived.

7.1 Performance Analysis of Path Loss Measurements

The measured path loss at any given distance \(d\) from the base station can be calculated from Eq. (5.3). Recalling the equation:

\[
PL_{mi} = ERP - P_{ri}
\]  

(7.1)
Where ERP (Effective Radiated Power) can be calculated as:

\[ ERP = P_{TX} + G_{TX} - CL_{TX} \]  \hspace{1cm} (7.2)

and \( P_{ri} \) (received power at the input of receive antenna) for the \( i \)th point can be calculated as:

\[ P_{ri} = RSL_i - G_{RX} + CL_{RX} \]  \hspace{1cm} (7.3)

Where:

\( P_{TX} \): Transmitted power in dBm

\( G_{TX} \): Gain of transmit antenna in dB

\( CL_{TX} \): Cable losses at transmission side in dB

\( RSL_i \): Received Signal Level for the \( i \)th point (receiver output) in dBm

\( G_{RX} \): gain of receive antenna in dB

\( CL_{RX} \): Cable losses at reception side in dB

The value of all these parameters were given in Table 6.5 except \( P_{ri} \) which can be obtained from measurements.

Figure 7.1 denotes the geographical location of measurement points of the first campaign and the location of the base station as well. Additionally, the figure
shows the corresponding measured RSL, given by (7.3), at each location for \( h=4 \) relay station antenna height.

![Map of RSL by Latitude & Longitude](image)

**Figure 7.1:** Received signal level by latitude and longitude

The path loss measurements from which the antenna pattern effects have been taken out are presented in Figure 7.2. Measurements are conducted for 1.7, 4, 8, 12 and 16 m of the receive antenna height. Free space path loss is plotted as well and as it is seen, it represents a lower boundary for the measurements. The path loss ranges from about 80 dB to about 180 dB for distances from 100 m to about 4 km. One can easily observe that the measurements show consistent trends. The increase
of path loss is a linear function of the log of distance. The figure shows clearly the effect of the relay antenna height on the path loss value in which these values decrease with the increase of relay antenna height. Measurements show less dependency of path loss value on the relay antenna height when the receiver is closer to the transmitter. This result may be explained by the fact that in such cases the receiver and the transmitter are in Line Of Sight (LOS) conditions in which relay antenna height does not have a significant impact on the received power. On the other hand, as the distance becomes larger, this dependency is more pronounced especially at lower relay antenna heights.

**Figure 7.2:** Measured and predicted path loss for different relay heights
The predicted path loss in [dB], solid lines in Figure 7.2, at any given distance $d$ from the transmitter with respect to a reference distance $d_0$ may be described as log-distance path loss model and given by:

$$PL(d) = PL_0 + m \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.4)

where $PL_0$ represents the intercept in [dB] and $m$ is the slope of the model in [dB/decade]. The intercept $PL_0$ is the path loss value at the reference distance $d_0$. The optimum values of $PL_0$ and $m$ were obtained according to the procedure explained in chapter 5, section 4. In this work, the reference distance $d_0$ was defined as 100 m.

Table 7.1 summarizes the obtained values of the slope $m$ and intercept $PL_0$ for different relay antenna heights. As seen, the slope and intercept are functions of the relay antenna height. For free space, $m=20$. However, as the path between transmitter and receiver gets obstructed, $m$ increases. In other words, $m$ increases as the receive antenna height decreases. It is intuitive that the slope gets closer to the free space value ($m=20$) as the relay antenna height is increased. The obtained values of $m$ are typical according to [35]. Similarly, the intercept $PL_0$ is inversely proportional to the relay antenna height.
### Table 7.1: Relay path loss propagation model parameters

<table>
<thead>
<tr>
<th>Relay height [m]</th>
<th>$PL_0$ [dB]</th>
<th>$m$ [dB/dec.]</th>
<th>$\sigma$ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>90.19</td>
<td>46.33</td>
<td>7.38</td>
</tr>
<tr>
<td>4</td>
<td>87.28</td>
<td>38.54</td>
<td>6.67</td>
</tr>
<tr>
<td>8</td>
<td>85.23</td>
<td>31.84</td>
<td>4.98</td>
</tr>
<tr>
<td>12</td>
<td>84.04</td>
<td>27.22</td>
<td>3.81</td>
</tr>
<tr>
<td>16</td>
<td>82.93</td>
<td>25.34</td>
<td>2.59</td>
</tr>
<tr>
<td>Free space</td>
<td>78.13</td>
<td>20</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 7.1 also shows the standard deviation ($\sigma$) of the prediction error between the predicted and measured path loss values.

In general, there are three parameters that describe the behavior and indicate the accuracy of prediction models. Firstly, the slope ($m$) of the model, which indicates how fast the path loss value increases as a function of distance. Secondly, the mean of prediction error ($\mu$), which is the difference between measured and predicted path loss value. This parameter is a log normally distributed random variable. Finally, the standard deviation ($\sigma$), which is a measure of the dispersion of the measured path loss from its local mean ($\mu$).

Note that the mean of prediction error ($\mu$) is equal to zero for the predicted path loss models. This is due to the fact that linear regression approach was used to develop those models and therefore the zero mean is obtained as a result of curve fitting.
More meaningful statistical parameter that describes the reliability of path loss models is the standard deviation ($\sigma$) of the prediction error.

Histograms in Figures 7.3 to 7.7 present the distribution of the prediction errors about their means for different relay antenna heights. It is observed that errors are almost log normally distributed about zero means with a standard deviation that decreases with the increase of the relay antenna height. It is noteworthy to point out that the variation of the path loss around its mean is due to the shadowing effect. This variation becomes smaller as the path between the transmitter and the receiver gets clearer. When the relay antenna height increases, the received signal experiences less attenuation, reflection or diffraction that caused by obstacles between transmitter and receiver. Therefore, the standard deviation of the received signal decreases as the relay antenna increases. The standard deviation, $\sigma$, ranges from 7.38 dB for the antenna height of 1.7 m to 2.59 dB for the highest relay height ($h=16$ m). These values of $\sigma$ are typical for suburban environment in which the measurements were conducted.
Figure 7.3: Distribution of prediction error for $h=1.7$ m

Figure 7.4: Distribution of prediction error for $h=4$ m
Figure 7.5: Distribution of prediction error for $h=8$ m

Figure 7.6: Distribution of prediction error for $h=12$ m
7.2 Path Loss Models at Different Relay Antenna Heights

According to the general path loss model given in (7.4) and propagation model parameters given in Table 7.1, one can write the propagation path loss model for any of the examined relay antenna heights. For example, in the case of \( h=1.7 \) m, the model is given as:

\[
PL(d) = 90.19 + 46.33 \log \left( \frac{d}{d_0} \right)
\]  

(7.5)
Similar to (7.5), other propagation models for the corresponding relay antenna heights 4 m, 8 m, 12 m, and 16 m can be expressed as well.

For the case of relay antenna height $h=4$ m, the model can be expressed as:

$$PL(d) = 87.28 + 38.54 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.6)

For the case of relay antenna height $h=8$ m, the model can be expressed as:

$$PL(d) = 85.23 + 31.84 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.7)

For the case of relay antenna height $h=12$ m, the model can be expressed as:

$$PL(d) = 84.04 + 27.22 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.8)

For the case of relay antenna height $h=16$ m, the model can be expressed as:

$$PL(d) = 82.93 + 25.34 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.9)

These models are valid for predicting path loss encountered in the relay link operates in 1900 MHz frequency band and distance ranges from 100-4000 m.
7.3 Received Signal Level models for Relay Stations

Similar to the predicted path loss formula given in (7.4), the predicted received signal level (RSL) at any given distance $d$ can be obtained as follows:

From (7.1), one may write

$$ RSL(d) = ERP - PL(d) \quad (7.10) $$

Substituting (7.4) into (7.10), one gets:

$$ RSL(d) = RSL_0 - m \log \left( \frac{d}{d_0} \right) \quad (7.11) $$

where

$$ RSL_0 = ERP - PL_0 \quad (7.12) $$

where $RSL_0$ in [dBm] is the received signal level at reference distance $d_0$. Table 7.2 summarizes the obtained values of the slope $m$ and intercept $RSL_0$ for the examined relay antenna heights.

Note that the values of the slope $m$ and $\sigma$ for different antenna heights are the same ones shown in Table 7.1. Comparing Table 7.1 and Table 7.2 one can observe that while $PL_0$ is decreasing with the increase of receive antenna height, $RSL_0$ is
increasing. The predicted and measured received signal level for the examined relay heights versus distance are plotted in Figure 7.8.

<table>
<thead>
<tr>
<th>Relay height [m]</th>
<th>$RSL_0$ [dBm]</th>
<th>$m$ [dB/dec.]</th>
<th>$\sigma$ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>-41.15</td>
<td>46.33</td>
<td>7.38</td>
</tr>
<tr>
<td>4</td>
<td>-38.44</td>
<td>38.54</td>
<td>6.67</td>
</tr>
<tr>
<td>8</td>
<td>-36.39</td>
<td>31.84</td>
<td>4.98</td>
</tr>
<tr>
<td>12</td>
<td>-35.20</td>
<td>27.22</td>
<td>3.81</td>
</tr>
<tr>
<td>16</td>
<td>-34.09</td>
<td>25.34</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Unlike the path loss, received signal level decreases with the increase of distance. The decrease of received signal level is a linear function of the log of distance. The figure also shows the impact of relay antenna height on the received signal values. The obtained results show that higher received signal level is achieved for higher relay antenna heights.

It is worthy to note that there are two different received antenna with different gains were used in this work. To show the effect of the relay antenna height on the received signal level and obtain fair comparison between measured and predicted values, the increase of the received signal due to antenna gain was removed. Therefore, the values in Figure 7.8 represent the predicted and measured received signal level just before the receive antenna.
Similar to path loss models, received signal level version of propagation models for the examined relay antenna heights can be presented. According to the model equation given in (7.11) and the model parameters provided in Table 7.2, RSL models can be expressed as follows.

For the case of relay antenna height $h=1.7$ m, the model can be given as:

$$RSL(d) = -41.15 - 46.33 \log\left(\frac{d}{d_0}\right)$$

(7.13)
For the case of $h=4$ m, the model can be written as:

$$RSL(d) = -38.44 - 38.54 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.14)

For the case of $h=8$ m, the model can be expressed as:

$$RSL(d) = -36.39 - 31.84 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.15)

For the case of $h=12$ m, the model can be given as:

$$RSL(d) = -35.20 - 27.22 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.16)

For the case of $h=16$ m, the model can be written as:

$$RSL(d) = -34.09 - 25.34 \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.17)

These models might be used to predict received signal level at relay stations operating in 1900 MHz band. The models are valid for distances between 100-4000 m from base station.
7.4 Path Loss Differences for the Examined Relay Heights

Studying and analyzing path loss differences between different relay antenna heights provide general understanding of the impact of relay antenna height on the path loss values. Additionally, it can be used to derive a correction factor for the relay antenna height. Consequently, instead of giving a path loss propagation model for each level of relay antenna height, one is able to derive a general propagation model that can predict the path loss for a range of relay heights. This can be achieved by introducing of the relay antenna height correction factor which will be discussed in the next section.

Table 7.3 shows the average path loss differences quantitatively in terms of their means and standard deviations for the examined relay antenna heights. Generally, higher relay antenna height provides smaller path loss. The smallest average reduction of path loss of 3.21 dB is obtained when the relay antenna height is changed from 12 to 16 m. Similarly, an average of 18.46 dB path loss difference is observed when the relay height is raised from 4 to 16 m. The standard deviation of the path loss differences ranges from 3.59 dB to 8.58 dB. Figure 7.9 to Figure 7.15 illustrate the distributions of the path loss differences for the examined relay antenna heights.
Table 7.3: Average of path loss differences between relay heights

<table>
<thead>
<tr>
<th>Path Loss Differences</th>
<th>Mean [dB]</th>
<th>Standard deviation [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL(h=1.7)-PL(h=4)</td>
<td>11.96</td>
<td>8.58</td>
</tr>
<tr>
<td>PL(h=4)-PL(h=8)</td>
<td>9.08</td>
<td>6.05</td>
</tr>
<tr>
<td>PL(h=8)-PL(h=12)</td>
<td>6.16</td>
<td>4.22</td>
</tr>
<tr>
<td>PL(h=4)-PL(h=12)</td>
<td>15.25</td>
<td>7.55</td>
</tr>
<tr>
<td>PL(h=12)-PL(h=16)</td>
<td>3.21</td>
<td>3.59</td>
</tr>
<tr>
<td>PL(h=8)-PL(h=16)</td>
<td>9.38</td>
<td>5.26</td>
</tr>
<tr>
<td>PL(h=4)-PL(h=16)</td>
<td>18.46</td>
<td>8.27</td>
</tr>
</tbody>
</table>

Figure 7.9: Distribution of path loss differences (PL(h=4) - PL(h=8))
Figure 7.10: Distribution of path loss differences (PL\(h=4\) - PL\(h=12\))

Figure 7.11: Distribution of path loss differences (PL\(h=8\) - PL\(h=12\))
Figure 7.12: Distribution of path loss differences (PL(h=8) - PL(h=16))

Figure 7.13: Distribution of path loss differences (PL(h=12) - PL(h=16))
Figure 7.14: Distribution of path loss differences (PL(h=4) - PL(h=16))

Figure 7.15: Distribution of path loss differences (PL(h=1.7) - PL(h=4))
7.5 Relay Antenna Height Correction Factor

It is of great interest to introduce the relay antenna height gain, or in other words, the path loss difference between different relay heights as a function of the receive antenna height. As it was mentioned, as the relay antenna height increases, there is, on average, improvement in the received signal level. This means also, path loss reduction is obtained as the relay antenna gets higher. An empirical path loss propagation model that takes into account the relay antenna height in suburban environment can be given into different formula according to the reference receive antenna height. If the reference receive antenna height \((h_{ref})\) is the height of the mobile station at the street level \((h=1.7 \text{ m})\), then the model can be given as:

\[
PL(d) = 90.19 + 46.33 \log\left(\frac{d}{d_0}\right) - \Delta h_m
\]  

(7.18)

If the reference receive antenna height is assumed to be the height of the relay station at \(h=4 \text{ m}\), then the model can be given as:

\[
PL(d) = 87.28 + 38.54 \log\left(\frac{d}{d_0}\right) - \Delta h_R
\]  

(7.19)

whereas \(\Delta h_m\) and \(\Delta h_R\) are the relay antenna height correction factors when \(h\) is different than the reference receive antenna height. In other words, \(\Delta h\) represents
the reduction of the path loss, or the improvement in the received signal level, as the result of the relay antenna height increase.

Based on Table 7.3, the average relay antenna height correction factor $\Delta h_m$ and $\Delta h_R$ may be approximated as:

$$\Delta h_m[\text{dB}] = 31.44 \log \left(\frac{h}{1.7}\right)$$ (7.20)

and

$$\Delta h_R[\text{dB}] = 31.1 \log \left(\frac{h}{4}\right)$$ (7.21)

for reference receive antenna height $h=1.7$ m and $h=4$ m, respectively. Equations (7.20) and (7.21) are based on the trends of the empirical relationship between the path loss differences as a function of the relay antenna height as provided in Table 7.3. These relationships along with the trend lines are graphically illustrated in Figure 7.16 and Figure 7.17. As can be seen from these figures, the trend line equations given in (7.20) and (7.21) show a very good fit with the measured path loss differences for the examined relay antenna heights.
Figure 7.16: Average relay antenna height correction factor ($\Delta h_m$) for $h_{ref}=1.7$ m

Figure 7.17: Average relay antenna height correction factor ($\Delta h_R$) for $h_{ref}=4$ m
Based on the propagation path loss models expressed in (7.18), (7.19) and antenna height correction factor expressed in (7.20) and (7.21), a general path loss prediction model for different relay antenna height can be given as follows.

For a reference antenna height \((h=1.7 \text{ m})\), the model is given as:

\[
PL(d) = 90.19 + 46.33 \log \left( \frac{d}{d_0} \right) - 31.44 \log \left( \frac{h}{1.7} \right) \quad (7.22)
\]

and for a reference antenna height \((h=4 \text{ m})\), the model is given as:

\[
PL(d) = 87.28 + 38.54 \log \left( \frac{d}{d_0} \right) - 31.1 \log \left( \frac{h}{4} \right) \quad (7.23)
\]

Propagation models given in (7.22) and (7.23) are to be used to predict the average path loss at any particular distance and for any given relay antenna height.

To the author's knowledge, \(\Delta h\) for most of propagation models is defined as a function either of only receiving antenna height \((h)\) or of both operating frequency \((f)\) and \(h\). However, when \(f\) is fixed, as in the study presented in this work, \(\Delta h\) becomes a function of \(h\) only. To this end, path loss models for all examined relay antenna heights based on the general model given by (7.22) and (7.23) are re-illustrated in Figure 7.18 and Figure 7.19, respectively.
As can be seen from the figures, path loss difference between any two relay antenna heights is now constant for the entire distance range. Some observations can be drawn from these figures. Firstly, it is observed that the obtained predicted path loss values for relay antenna heights different than the reference height are different from the actual path loss (compare to measurements in Figure 7.2). Secondly, model predictions seem to be very optimistic when the relay station is close to the base station. Some of them even show less path loss values than the free space model which is not realistic.

**Figure 7.18:** Path loss models based on the average relay antenna height correction factor for $h_{ref}=1.7$ m
Figure 7.19: Path loss models based on the average relay antenna height correction factor for $h_{ref}=4$ m

Additionally, the models overestimate the predicted path loss when the relay station is far from the base station. Finally, the intercept ($PL_0$) and slope ($m$) of these models are also different from that obtained from measurements and summarized in Table 7.1.

For more illustrations, Figure 7.20 presents the error between the actual model predictions and the ones that are based on the implementation of the average relay antenna height correction factor for $h_{ref}=1.7$ m.
Figure 7.20: Prediction error based on the average relay antenna height correction factor ($\Delta h_m$) for $h_{ref}=1.7$ m

From Figure 7.20, one can see that the implementation of the average relay antenna height results in tolerant errors only when the distance is between about 1000 m and 1500 m. In this range, the error is less than 2 dB. However, for smaller and larger distances, the error increases rapidly especially for high relay antenna heights. It is noteworthy to mention that positive value of the error means that the model underestimates the actual path loss value. On the contrary, negative values indicate that the model over predicts the path loss.
Likewise, Figure 7.21 shows model prediction errors based on the implementation of relay antenna height in the case of $h_{ref}=4$ m.

**Figure 7.21**: Prediction error based on the average relay antenna height correction factor ($\Delta h_R$) for $h_{ref}=4$ m

Prediction errors show the same trend as for $h_{ref}=1.7$ m except for the case when the relay antenna height ($h=1.7$ m) is smaller than the reference antenna height ($h_{ref}=4$ m). In this case, the model over estimates the path loss values for short distances and vice versa.
From Figure 7.20 and Figure 7.21, it is clear that the implementation of the average relay antenna height correction factors given in (7.20) and (7.21) which take only the relay height into consideration is not the appropriate approach to develop a general empirical path loss propagation model. This is because of the large obtained prediction errors as a result of this approach.

From the previous discussion, it is obvious that one or more parameters need to be taken into account when evaluating \( \Delta h \). Measurements show, as it was presented in Figure 7.2, that \( \Delta h \) is not only a function of relay antenna height (\( h \)) but it is also a linear function of the log of distance (\( d \)).

To understand and derive the relationship between \( \Delta h \) and distance, following simple scenario is considered. According to the measurements (refer to Figure 7.2), any two path loss models that have different relay antenna height \( h_1 \) and \( h_2 \), models might be given as:

\[
PL_{1,2}(d) = PL_{01,02} + m_{1,2} \log \left( \frac{d}{d_0} \right)
\]  

(7.24)

where \( h_1 > h_2, m_1 < m_2, PL_{01} < PL_{02} \).

Figure 7.22 illustrates the models expressed in (7.24).
Figure 7.22: Illustration of $\Delta h$ as a function of relay height and distance

As can be seen from Figure 7.22, the antenna height correction factor $\Delta h$ is no longer constant between any two particular path loss models as it was shown in Figure 7.18 and Figure 7.19. $\Delta h$, however, increases as a linear function of the log of distance $d$. The path loss difference $\Delta PL$ at any particular distance for two different antenna heights which is also equal to $\Delta h$ can be given as:

$$\Delta PL = \Delta h = x \log\left(\frac{h_1}{h_2}\right) = \Delta PL_0 + \Delta m \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.25)

where $\Delta PL_0 = PL_{02} - PL_{01}$, $\Delta m = m_2 - m_1$ and $x$ is the slope of the antenna height dependence that needs to be determined.
To generalize the expression given in (7.25), \( h_2 \) will be considered as \( h_{\text{ref}} \) and 
\( h_1 \) can be any value of the examined relay antenna heights \( (h) \). Therefore, the value of \( x \) may be calculated as:

\[
x[\text{dB}] = \frac{\Delta m \log \left( \frac{d}{d_0} \right) + \Delta PL_0}{\log \left( \frac{h}{h_{\text{ref}}} \right)}
\]  

(7.26)

Two reference antenna heights will be considered for the derivation of the antenna height correction factor \( \Delta h \). Note that the goal of determining \( \Delta h \) is to find a general path loss model that can be used for any relay antenna height relative to a reference antenna height. The two reference antenna heights are \( h_{\text{ref}}=4 \) m and \( h_{\text{ref}}=1.7 \) m. Table 7.4 and Table 7.5 show the values of \( \Delta m \) and \( \Delta PL_0 \) for the examined relay heights in the cases of \( h_{\text{ref}}=4 \) m and \( h_{\text{ref}}=1.7 \) m, respectively.

**Table 7.4**: Slope and intercept differences for \( h_{\text{ref}}=4 \) m

<table>
<thead>
<tr>
<th>( h ) [m]</th>
<th>( PL_0 ) [dB]</th>
<th>( \Delta PL_0 ) [dB]</th>
<th>( m ) [dB/dec]</th>
<th>( \Delta m ) [dB/dec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>90.19</td>
<td>-2.91</td>
<td>46.33</td>
<td>-7.79</td>
</tr>
<tr>
<td>4</td>
<td>87.28</td>
<td>0</td>
<td>38.54</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>85.23</td>
<td>2.05</td>
<td>31.84</td>
<td>6.7</td>
</tr>
<tr>
<td>12</td>
<td>84.04</td>
<td>3.24</td>
<td>27.22</td>
<td>11.32</td>
</tr>
<tr>
<td>16</td>
<td>82.93</td>
<td>4.35</td>
<td>25.34</td>
<td>13.2</td>
</tr>
</tbody>
</table>
### Table 7.5: Slope and intercept differences for $h_{ref}=1.7$ m

<table>
<thead>
<tr>
<th>$h$ [m]</th>
<th>$PL_0$ [dB]</th>
<th>$\Delta PL_0$ [dB]</th>
<th>$m$ [dB/dec]</th>
<th>$\Delta m$ [dB/dec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>90.19</td>
<td>0</td>
<td>46.33</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>87.28</td>
<td>2.91</td>
<td>38.54</td>
<td>7.79</td>
</tr>
<tr>
<td>8</td>
<td>85.23</td>
<td>4.96</td>
<td>31.84</td>
<td>14.49</td>
</tr>
<tr>
<td>12</td>
<td>84.04</td>
<td>6.15</td>
<td>27.22</td>
<td>19.11</td>
</tr>
<tr>
<td>16</td>
<td>82.93</td>
<td>7.26</td>
<td>25.34</td>
<td>20.99</td>
</tr>
</tbody>
</table>

Now, the task is to find the value of $x$ that was expressed in (7.26) for all examined relay heights ($h$) for the two reference cases.

### 7.5.1 For the case $h_{ref}=4$ m:

Considering (7.26) and Table 7.4, $x$ for different relay heights can be given as:

- For $h=1.7$ m

\[
x[\text{dB}] = 20.96 \log \left( \frac{d}{d_0} \right) + 7.83
\]  

(7.27)

- For $h=8$ m

\[
x[\text{dB}] = 22.26 \log \left( \frac{d}{d_0} \right) + 6.81
\]  

(7.28)
• For $h=12$ m

\[ x[\text{dB}] = 23.72 \log \left( \frac{d}{d_0} \right) + 6.79 \]  

(7.29)

• For $h=16$ m

\[ x[\text{dB}] = 21.92 \log \left( \frac{d}{d_0} \right) + 7.23 \]  

(7.30)

To find the value of $x$ that might be used for different relay heights, it turns out that taking the average of $x$ is the appropriate approach to determine this value. Thus, the mean value of $x$ is given by:

\[ x[\text{dB}] = 22.21 \log \left( \frac{d}{d_0} \right) + 7.17 \]  

(7.31)

By substituting (7.31) into (7.25), the antenna height correction factor is now can be given as:

\[ \Delta h = \left[ 22.21 \log \left( \frac{d}{d_0} \right) + 7.17 \right] \log \left( \frac{h}{4} \right) \]  

(7.32)

Equation (7.32) has two coefficients, 22.21 and 7.17, that are dependent on the environment. $\Delta h$ is illustrated graphically in Figure 7.23. This figure presents a family of curves of $\Delta h$ as a function of distance ($d$) for different relay antenna
heights \( (h) \). The figure clearly shows the dependency of \( \Delta h \) on the distance between the transmitter and the relay station. This dependency is especially pronounced for high relay heights. For instance, in the case \( h=16 \) m, \( \Delta h \) increases from less than 5 dB at \( d=100 \) m to about 26 dB at \( d=4000 \) m. Even though the increase in \( \Delta h \) is relatively smaller (from about 1 dB to 7.5 dB) in the case of \( h=6 \) m, the changes in \( \Delta h \) confirms that \( \Delta h \) is not only function of relay height \( (h) \) but also function of distance.

**Figure 7.23**: Relay antenna height correction factor \( (\Delta h) \) as a function of distance and relay height
Thus, (7.32) and Figure 7.23 help explain how it is very important to take into account the distance dependency when considering the relay antenna height correction factor. This dependency has a great effect on the predicted path loss value and therefore on the model accuracy. Lack of this consideration might lead to very large errors in path loss predictions as it was explained earlier.

Note that the goal of finding an empirical path loss model that takes into account the relay antenna height correction factor has been achieved. This model is expressed as:

$$PL(d) = 87.28 + 38.54 \log\left(\frac{d}{d_0}\right) - \Delta h$$  \hspace{1cm} (7.33)

where $\Delta h$ is given as in (7.32).

To verify the validity of the path loss model proposed in (7.33) after the implementation of $\Delta h$, a comparison between the model predictions and the measurements is shown in Figure 7.24.
Figure 7.24: Measurements compared to model predictions after implementation of $\Delta h$ for $h_{ref}=4$ m

One can notice that the measurements are in good agreement with the model predictions. Checking the accuracy of the model predictions after the introduction of the antenna height correction factor $\Delta h$ is achieved by comparing Figure 7.2 (before implementation of $\Delta h$) and Figure 7.24 (after implementation of $\Delta h$). One can see that the model predictions in both cases are very similar with negligible prediction error. Table 7.6 provides this comparison quantitatively in terms of the mean value of the prediction error ($\mu$) and the standard deviation ($\sigma$). It is apparent from this table that implementation of the antenna height correction factor does not affect the agreement with the measurements. Since the path loss model for relay
height equal to 4 m was taken as a reference for other models, there is no change in its \( \mu \) and \( \sigma \) before and after implementation of antenna height correction factor.

### Table 7.6: Model comparison before and after implementation of \( \Delta h \) relative to the measurements for \( h_{ref} = 4 \) m

<table>
<thead>
<tr>
<th>( h ) [m]</th>
<th>Mean ( \mu ) [dB]</th>
<th>Standard deviation ( \sigma ) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>1.7</td>
<td>0</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0.78</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0.15</td>
</tr>
</tbody>
</table>

After the determination of the relay antenna height correction factor, it is of great interest to show how the slope \( m \) and the intercept \( PL_0 \) of relay path loss propagation model change with the relay height. To derive the relationship between the model parameters \( (m \) and \( PL_0 \)) and the relay height \( (h) \), (7.33) is to be reconsidered. Rewriting (7.33) with the associated \( \Delta h \) given in (7.32), one may get:

\[
PL(d) = 87.28 + 38.54 \log \left( \frac{d}{d_0} \right) - 22.21 \log \left( \frac{d}{d_0} \right) \log \left( \frac{h}{4} \right) - 7.17 \log \left( \frac{h}{4} \right)
\]  

(7.34)
Obtaining the intercept \( PL_0 \) and the slope \( m \) as a function of relay antenna height \( h \) can be done as follows.

Firstly, to express \( PL_0 \) as a function of \( h \), \( d \) is assumed to be equal to \( d_0 \) in (7.34). Therefore,

\[
PL_0(h) = 87.28 - 7.17\log\left(\frac{h}{4}\right)
\]  

(7.35)

Similarly, to express \( m \) as a function of \( h \), the intercept terms in (7.34), namely the first and last terms, are to be eliminated. Additionally, \( \log \left( \frac{d}{d_0} \right) \) in (7.34) needs to be equal to one. Therefore,

\[
m(h) = 38.54 - 22.21\log\left(\frac{h}{4}\right)
\]  

(7.36)

Figure 7.25 and Figure 7.26 compare \( PL_0 \) and \( m \) obtained from the last two relationships to the ones achieved by the measurements presented in Table 7.1. The figures show that both intercept path loss and slope decrease with the increase of relay antenna height. Additionally, figures indicate that for every doubling in relay antenna height there is a decrease of 2.15 dB in intercept and 6.69 dB/decade in slope.
Figure 7.25: Intercept ($PL_0$) as a function of relay antenna height

Figure 7.26: Slope ($m$) as a function of relay antenna height
Formulas given in (7.35) and (7.36) represent mathematical expressions by which one can calculate the intercept ($PL_0$) and slope ($m$) for any given relay antenna height ranging from 2 to 16 m.

Thus, another approach of developing empirical propagation path loss models for relay environment has been achieved. This model might be given as:

$$PL(d) = PL_0(h) + m(h) \log\left(\frac{d}{d_0}\right)$$  \hspace{1cm} (7.37)

where $PL_0(h)$ and $m(h)$ can be calculated by (7.35) and (7.36), respectively.

To prove the validity of the model given in (7.37), a comparison between model predictions and measurements is made in Table 7.7.

**Table 7.7:** Comparison between measurements and model predictions

<table>
<thead>
<tr>
<th>$h$ [m]</th>
<th>Measurements</th>
<th>Model predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$PL_0$ [dB]</td>
<td>$m$ [dB/dec]</td>
</tr>
<tr>
<td>1.7</td>
<td>90.19</td>
<td>46.33</td>
</tr>
<tr>
<td>4</td>
<td>87.28</td>
<td>38.54</td>
</tr>
<tr>
<td>8</td>
<td>85.23</td>
<td>31.84</td>
</tr>
<tr>
<td>12</td>
<td>84.04</td>
<td>27.22</td>
</tr>
<tr>
<td>16</td>
<td>82.93</td>
<td>25.34</td>
</tr>
</tbody>
</table>
As may be seen from Table 7.7, model predictions and model parameters are in good agreement with the ones that obtained by the measurements. Therefore, the statistical propagation model expressed in (7.37) with its associated parameters $PL_0(h)$ and $m(h)$ given in (7.35) and (7.36) may be used to predict the path loss at any particular distance for relaying scenarios in suburban areas.

### 7.5.2 For the case $h_{ref}=1.7$ m:

Considering (7.26) and Table 7.5, $x$ for different relay heights can be given as:

- For $h=4$ m

  \[ x[\text{dB}] = 20.96 \log \left( \frac{d}{d_0} \right) + 7.83 \]  
  \[ (7.38) \]

- For $h=8$ m

  \[ x[\text{dB}] = 21.54 \log \left( \frac{d}{d_0} \right) + 7.37 \]  
  \[ (7.39) \]

- For $h=12$ m

  \[ x[\text{dB}] = 22.52 \log \left( \frac{d}{d_0} \right) + 7.23 \]  
  \[ (7.40) \]

- For $h=16$ m
\[ x[\text{dB}] = 21.56 \log\left(\frac{d}{d_0}\right) + 7.46 \quad (7.41) \]

With the same approach followed in the previous case \((h_{ref}=4 \, \text{m})\), the average value of \(x\) might be given as:

\[ x[\text{dB}] = 21.65 \log\left(\frac{d}{d_0}\right) + 7.48 \quad (7.42) \]

To find \(\Delta h\) for the case of \(h_{ref}=1.7 \, \text{m}\), one needs to substitute (7.42) into (7.25). Therefore,

\[ \Delta h = \left[ 21.65 \log\left(\frac{d}{d_0}\right) + 7.48 \right] \log\left(\frac{h}{1.7}\right) \quad (7.43) \]

Taking \(\Delta h\) into account, the empirical path loss model when reference antenna height is equal to 1.7 m is given as:

\[ PL(d) = 90.19 + 46.33 \log\left(\frac{d}{d_0}\right) - \Delta h \quad (7.44) \]

where \(\Delta h\) is given as in (7.43).

If one were to plot path loss curves using (7.36) for \(h=1.7, 4, 8, 12\) or 16 meter, one would obtain similar curves to those presented in Figure 7.2 with negligible error.
Table 7.8 provides a comparison between the models before and after implementing the antenna height correction factor relative to the measurements. Ones again, it is clear from the table that implementation of $\Delta h$ has no effect on the agreement with the measurements.

**Table 7.8**: Model comparison before and after implementation of $\Delta h$ relative to the measurements for $h_{\text{ref}}=1.7$ m

<table>
<thead>
<tr>
<th>$h$ [m]</th>
<th>Mean $\mu$ [dB]</th>
<th>Standard deviation $\sigma$ [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>1.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-0.16</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>-0.02</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0.78</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0.18</td>
</tr>
</tbody>
</table>

From the results in Table 7.6 and Table 7.8, it turns out that regardless of which one of reference antenna heights ($h_{\text{ref}}=1.7$ or 4 m) is used, path loss models proposed in (7.33) and (7.44) can perform with approximately the same accuracy. Therefore, those proposed models along with the associated $\Delta h$ present general propagation models. Either one of those models might be used to predict the path loss value at any particular distance for any given relay station antenna height between 4 m and 16 m which is a suitable range of relay antenna height and within environment similar to one surveyed in the measurement campaign.
Chapter 8: Developed Path Loss Models for Relaying Systems

In chapter 4, a number of propagation models were discussed. They can be grouped by their applicability in relaying systems. While the models in the first group, namely 3GPP model, WINNER B5f model and IEEE802.16j model were specifically developed for relaying deployment, the models in the other group were not. However, because they are widely used propagation models for planning cellular networks, it is of great interest to establish a relationship between measurements and some of these standard propagation models. Well known examples of those models are Lee model and COST231-Hata model. In this chapter, the validity of the above mentioned models is evaluated by comparing their performance with measurements [48-50]. Note that the evaluation is limited to the prediction of path loss encountered on the backhaul link only. Additionally, some modifications of the original forms of the discussed models are introduced to make their predictions more reliable in relay environments.

8.1 Performance Analysis of Existing Models

The validity of existing propagation models is examined by comparing their path loss predictions to the measurements. Each individual propagation model has
its own set of assumptions and is restricted to a specific range of parameters under which it was derived.

8.1.1 Corresponding Assumptions for Considered Models

For each propagation model, the following assumptions are considered when those models are used to predict path loss. More information about these models are available in chapter 4.

For the case of 3GPP model, NLOS condition was assumed since the link between the base station and the relay station (backhaul link) was obstructed by buildings and trees at most of the measurement locations. The model is given by [8]:

\[
PL_{3GPP}[\text{dB}] = 125.2 + 36.3 \log(d)
\]  

(8.1)

where \( d \) in [km] is the eNodeB-relay separation.

Among the proposed models by WINNER II is the WINNER B5f which is the most appropriate model for the prediction of the path loss on a backhaul link. WINNER B5f model takes into account both LOS and NLOS conditions where the eNodeB antenna height is above the rooftop level and the relay station antenna height is either above or below the rooftop level. WINNER B5f model is given by [14]:

124
\[ PL_{\text{WINNER B5f}}[\text{dB}] = 57.5 + 23.5 \log(d) + 23 \log\left(\frac{f}{5}\right) \]  \hspace{1cm} (8.2)

where \( d \) in [m] is the distance and \( f \) in [GHz] is the frequency.

In the case of IEEE802.16j model [15], terrain type “B” with constants \( a = 4.0, b = 0.0065 \) and \( c = 17.1 \) was considered as the most suitable one for the environment in which the measurements were collected. The general model formula is given as:

\[ PL_{\text{IEEE802.16j}}[\text{dB}] = A + 10\gamma \log\left(\frac{d}{d_0}\right) + \Delta PL_f + \Delta PL_h \]  \hspace{1cm} (8.3)

where the model parameters were already defined in section 4.3.3.5.

Note that for the case of COST231-Hata model, "suburban environment" category with receive antenna height correction factor \( a (h_m) \) for small to medium city was used. COST231-Hata model equation is given by [44]:

\[ PL_{\text{COST231-Hata}}[\text{dB}] = A + B \log(d) + C_m + a(h_m) \]  \hspace{1cm} (8.4)

where \( A, B, d, C_m \) and \( a(h_m) \) were defined in section 4.3.3.4.

For the case of Lee model, corresponding values of slope and intercept for "suburban area" were assumed. The model is provided relative to reference conditions and is given as [41]:

125
\[ PL_{\text{Lee}} = PL_0 + m \log \left( \frac{d}{d_0} \right) - 15 \log \left( \frac{h_t}{h_{\text{tref}}} \right) - 10 \log \left( \frac{h_r}{h_{\text{rref}}} \right) \]  \hspace{1cm} (8.5)

where all Lee model parameters were defined in section 4.3.3.2.

Finally, for the new relay model proposed in [21], there are no assumptions to consider and therefore the model is given as:

\[ PL_{\text{Relay model}}[\text{dB}] = 34 \log(d) + 5 + 26 \log(20 - h_{RS}) \]  \hspace{1cm} (8.6)

where \( h_{RS} \) in [m] is the relay antenna height.

### 8.1.2 Simplified Versions of Existing Models

In the following, each individual propagation model performance relative to the measurements is discussed. To make the comparison more explicatory, each propagation model is expressed in a simplified form. In other words, model equations given by (8.1) - (8.6) are simplified into a general path loss model formula that is given as:

\[ PL[\text{dB}] = PL_0 + m \log \left( \frac{d}{d_0} \right) + \Delta h \]  \hspace{1cm} (8.7)

where \( PL_0 \) is the path loss value at \( d_0=100 \) m, \( m \) is the slope, \( d \) is the distance in meters and \( \Delta h \) in decibel is the relay antenna height correction factor which allows to predict path loss for different relay heights. To express each model in the
simplified form given by (8.7), all models’ parameters are replaced with their actual values. Corresponding parameters values for the considered models are summarized in Table 8.1.

Table 8.1: Models parameters assumptions for measurement campaign

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All models</td>
<td>Frequency</td>
<td>1925 MHz</td>
</tr>
<tr>
<td></td>
<td>Transmit antenna height</td>
<td>25.5 m</td>
</tr>
<tr>
<td></td>
<td>Receive antenna height</td>
<td>4, 8, 12, 16 m</td>
</tr>
<tr>
<td>IEEE802.16j</td>
<td>Terrain type B</td>
<td>$a=4$, $b=0.0065$, $c=17.1$</td>
</tr>
<tr>
<td>COST231-Hata</td>
<td>Environment</td>
<td>suburban</td>
</tr>
<tr>
<td></td>
<td>$a$ ($h_m$)</td>
<td>Eq. (4.15)</td>
</tr>
<tr>
<td></td>
<td>$C_m$</td>
<td>0 dB</td>
</tr>
<tr>
<td>Lee</td>
<td>$m$</td>
<td>38.4 dB/dec</td>
</tr>
<tr>
<td></td>
<td>$PL_0 @ f=1925$ MHz</td>
<td>114.3 dB</td>
</tr>
<tr>
<td></td>
<td>$h_{tref}$</td>
<td>30.48 m</td>
</tr>
<tr>
<td></td>
<td>$h_{rref}$</td>
<td>3.048 m</td>
</tr>
<tr>
<td>3GPP</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>WINNER B5f</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Relay model [21]</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Regarding Lee model, note that $PL_0$ at $f=1925$ MHz was calculated according to Table 4.3 and Eq. (4.13). After substituting of all parameters values in equations (8.1) to (8.6), each individual simplified model formula is now can be determined. Note that for all considered propagation models the relay antenna height in [m] is replaced with the parameter $h$. Additionally, parameter "$d$" is expressed in meters for all models. After these basic adjustments, the model equations become as follows.

For 3GPP model:

$$PL_{3GPP}[\text{dB}] = 88.9 + 36.3 \log\left(\frac{d}{d_0}\right) + \Delta h_{3GPP} \quad (8.8)$$

where $\Delta h_{3GPP}=0$.

For WINNER B5f model:

$$PL_{WINNER \; B5f}[\text{dB}] = 94.97 + 23.5 \log\left(\frac{d}{d_0}\right) + \Delta h_{WINNER \; B5f} \quad (8.9)$$

where $\Delta h_{WINNER \; B5f}=0$.

For IEEE802.16j model:

$$PL_{IEEE802.16j}[\text{dB}] = 78.07 + 45 \log\left(\frac{d}{d_0}\right) - 11.12 \log\left(\frac{h_r}{3}\right) \quad (8.10)$$
For COST231-Hata model:

\[ PL_{COST231-Hata} [\text{dB}] = 106.83 + 35.69 \log \left( \frac{d}{d_0} \right) - 2.91 h_r \] (8.11)

For Lee model:

\[ PL_{Lee} [\text{dB}] = 73.97 + 38.4 \log \left( \frac{d}{d_0} \right) - 10 \log (h_r) \] (8.12)

For relay model [21]:

\[ PL_{Relay \ model} [\text{dB}] = 73 + 34 \log \left( \frac{d}{d_0} \right) + 26 \log (20 - h_{RS}) \] (8.13)

It is worth noting that equations (8.8) to (8.13) represent just a simplified versions of the original forms of models without any further modifications. As far as the performance of the considered models is concerned, a number of observations can be pointed out. As can be seen from the previous model equations, the slope (m) of each individual model is constant and does not depend on relay antenna height. Furthermore, it is apparent that relay model, COST-Hata, 3GPP, Lee models exhibit similar slope values, namely, 34, 35.69, 36.3 and 38.4 dB/dec, respectively which are closer to the ones obtained from the measurements presented in the previous chapter. On the contrary, WINNER B5f and IEEE802.16j models manifest completely different slopes. While for WINNER B5f model
\( m=23.5 \) is relatively small compared to the measurements, for IEEE802.16j model \( m=45 \) is quite large.

### 8.1.3 Graphical and Statistical Evaluation

Figure 8.1 to Figure 8.4 show the path loss predictions obtained by the existing models for different relay antenna heights \( (h) \), namely 4, 8, 12 and 16 m versus the distance between the eNodeB and the relay station. In fact, the illustrated models performance demonstrate the footprint of previous simplified models equations. Additionally, the figures illustrate the path loss obtained by the measurements for the examined relay heights.

One general observation from the figures is that the path loss is a linear function of the log of the distance. Another observation is that there is a clear trend of decreasing path loss values with the increase of the relay antenna height and therefore the intercept \( (PL_0) \) is smaller for higher relay heights. This trend is observed for the measurements and all six models except for 3GPP and WINNER B5f models. These two models were developed just for fixed relay heights and therefore they do not associate antenna height correction factor \( (\Delta h) \) with their original forms. As a result, path loss predictions made by those two models remain the same for all relay heights. As far as the slope \( (m) \) is concerned, all considered models manifest the same slope for different examined relay heights. In other words, the slope of those models is antenna-height independent. However, as it was
explained in the previous chapter, the measurements show a clear evidence that path loss models should be antenna-height dependent. This trend is clearly observed in the figures.

**Figure 8.1:** Comparison of model predictions with measurements for $h=4$ m
Figure 8.2: Comparison of model predictions with measurements for $h=8$ m

Figure 8.3: Comparison of model predictions with measurements for $h=12$ m
Figure 8.4: Comparison of model predictions with measurements for $h=16$ m

Even though graphs give general understanding on how a propagation model behaves compared to measurements, statistical analysis provides more information about the accuracy of model predictions. The metrics used for the evaluation of propagation models are the mean of the prediction error ($\mu$) and the standard deviation ($\sigma$) of this error. The prediction error is defined as the difference between model predictions and the measurements. Additionally, the standard deviation represents the dispersion of the measured path loss from model prediction.

The model accuracy is measured through prediction error. Ideally, the prediction error has a zero mean (unbiased model) and the standard deviation that is
close to zero (good accuracy model). To this end, Table 8.2 compares the results obtained for different propagation models relative to the measurements. It is noteworthy to point out that a positive value of \( \mu \) of a model means that the model on average overestimates the path loss value, i.e. the model is pessimistic. Negative values indicate that the predicted path loss is smaller than expected. Likewise, a small value of \( \sigma \) indicates a good model prediction, while a large value demonstrates less model accuracy. As can be seen from Table 8.2, generally, none of the model agrees well with the measurements.

<table>
<thead>
<tr>
<th>Model</th>
<th>Metric [dB]</th>
<th>Relay height ((h)) in [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3GPP</td>
<td>( \mu )</td>
<td>-0.92</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>6.71</td>
</tr>
<tr>
<td>WINNER B5f</td>
<td>( \mu )</td>
<td>-9.37</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>8.27</td>
</tr>
<tr>
<td>IEEE802.16j</td>
<td>( \mu )</td>
<td>-3.25</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>7.00</td>
</tr>
<tr>
<td>COST231-Hata</td>
<td>( \mu )</td>
<td>4.65</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>6.74</td>
</tr>
<tr>
<td>Lee</td>
<td>( \mu )</td>
<td>-19.51</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>6.67</td>
</tr>
<tr>
<td>Relay model [21]</td>
<td>( \mu )</td>
<td>11.88</td>
</tr>
<tr>
<td></td>
<td>( \sigma )</td>
<td>6.83</td>
</tr>
</tbody>
</table>
8.1.4 Individual Evaluation of Existing Models

In the following, performance of each individual propagation model is compared to the measurements and considered separately. As Table 8.2 shows, while for \( h = 8, 12 \) and \( 16 \) 3GPP model significantly over predicts the path loss values, the model matches the measurements with small \( \mu \) of 0.92 dB for \( h=4 \). This result may be explained by the fact that 3GPP model was developed under assumptions similar to the \( h=4 \) case presented in this work. The 3GPP model was developed for frequency of 2GHz, base station antenna height of 30 m and relay height of 5 m. On the other hand, the lack of relay antenna height correction factor of 3GPP model for heights different than 4 m leads to the mismatch between model predictions and measurements in the cases of \( h =8, 12 \) and \( 16 \) m. The model accuracy ranges from 4.81 to 6.71 dB. As a final comment, in the case of \( h=4 \) m, results show that 3GPP model is the best candidate among other models.

Consider now WINNER B5f model. Even though it gives the lowest prediction error (\( \mu=1 \) dB) in the case of \( h=8 \) m, the model badly predicts the path loss when compared with measured data for all relay heights. Having a small \( \mu \) does not necessarily mean that the model prediction matches the measurements because the error is averaged over the entire measurements. Therefore, the error statistics are not an appropriate evaluation metric in such cases. To evaluate the model prediction under similar circumstances, one should consider graphical performance illustration instead (see Figure 8.2). This figure clearly shows the
mismatch between the measurements and the model prediction. This is due to the fact that WINNER B5f model has relatively small slope value compared to the measurements and other models. Nevertheless, it is apparent from Figure 8.4 ($h=16$ m) that if model predictions had been shifted down by some value, they would have followed the measurements. According to Table 8.2, this shift is 10.38 dB which is the mean of the prediction error. Except for this shift, there is an agreement between the model predictions and the measurements with very small standard deviation of 2.28 dB. This result could be attributed to the fact that there is a similarity in the assumptions between measurements and WINNER B5f model. It seems possible that the model over estimates the actual path loss values by 10.38 dB, on average, because WINNER B5f model was designed for urban relaying cellular scenarios and not for suburban ones where the measurements were carried out. Similar to 3GPP model, WINNER B5f model was developed for a certain level of relay height and does not provide an antenna height correction factor. For this reason model predictions remain the same for all relay height levels. Therefore, path loss predictions made by WINNER B5f are not reliable especially for relay heights lower than 16 m. Such discrepancy with measured data is also highlighted in previous studies and reported in [21].

Concerning now IEEE802.16j model. Unlike the 3GPP and WINNER B5f models, this model has a correction factor for the relay antenna height. Nevertheless, the model predictions are incoherent with the measurements. This
incoherence is pronounced and can be easily seen for the higher levels of relay heights (see Figure 8.3 and Figure 8.4). Quantitatively, this is also clear since both μ and σ are relatively large and more than 6 dB and 7 dB, respectively for relay heights greater than 10 m. This is because the model is not valid for relay heights greater than 10 m. For relay heights 4 and 8 m, the model underestimates the actual path loss especially for distances closer to the transmitter (Figure 8.1 and Figure 8.2). It is clear from the previous figures that the model exhibits quit large slope (m=45 dB/decade) compared to the measurements. It is somewhat surprising that even for relay heights lower than 10 m for which antenna height correction factor was provided, the model predictions do not match the measurements. This was unexpected because the model was proposed for relaying scenarios. This conclusion of mismatch between IEEE802.16j model predictions and measurements supports the finding in the previous study [21] which ended up with the same conclusion.

Even though COST231-Hata model provides receive antenna height correction factor, its prediction, in general, is not in a good agreement with the measurements. While the model over predicts the path loss for lower relay heights, its underestimation is noticeable for higher relay heights. However, the model predictions for medium relay heights, namely h=8 m and h=12 m, are much better. The average prediction error is between 2.5 and 3 dB for medium relay heights and the model accuracy ranges from 4 to 5 dB. For the case when h=16 m, the average
error exceeds 11 dB. A possible explanation for this might be that the associated antenna height correction factor for the COST231-Hata model is not valid for heights beyond 10 m. In general, the mismatch with the measurements for all relay heights is due the fact that COST231-Hata model does not take the clutter and terrain profile into account. In addition, the model is an extension version of Hata model which was developed in Japanese and European cities. In general, these cities tend to have different clutter and terrain profile than US cities. Another possible explanation for the observations is that COST231-Hata model is most appropriate for mobile scenarios rather than relaying deployment where typical antenna heights are between 4 and 16 m.

Turning now to Lee model. The model seems to be very optimistic in predicting path loss. The average prediction error exceeds 19 dB for the lowest relay height and it is about 7 dB for the highest one as it shown in Table 8.2. Even though the model gives very large error for the case when \( h=4 \) m, the slope of the model \( (m=38.4 \text{ dB/dec.}) \) is very close to the one obtained from the measurements \( (m=38.54 \text{ dB/dec.}) \) as it can be seen from Figure 8.1. In other words, if Lee model curve had been shifted up by the average error value \( (\mu=19.51 \text{ dB}) \), it would have matched the measurements. Except for this shift, there is an agreement between the model predictions and the measurements with a standard deviation \( (\sigma) \) of 6.67 dB. Note that this value of \( \sigma \) is exactly the same one obtained from the measurements.
This indicates that the accuracy of the model proposed for $h=4$ m in this study is similar to Lee model's accuracy.

Finally, the relay model proposed in [21] which was designed for relay link over predicts the actual path loss at all relay heights. The prediction error ranges from 15 dB to about 20 dB. The standard deviation of the error is between 4 dB and 7 dB. The mismatch with the measurements is due to the constraints that are associated with the relay model. Among the constraints is the difference in the environment in which both measurement campaigns were conducted. While the measurements in the presented research were performed in suburban environment, the relay model was designed for relaying deployment in urban one. Additionally, the model is valid for distances that are much shorter compared to the ones proposed in this work, namely 1000 m versus 4000 m. It can be concluded that since the relay model proposed in [21] was designed for relay link in NLOS conditions in urban environment, its applicability in different area is not valid.

### 8.2 Tuning of Existing Models

As it was mentioned in the introduction of this chapter, the considered existing propagation models might be divided into two groups according to their applicability in relaying deployment. Those two groups are standard models for cellular networks and models which were specifically developed for relaying scenarios. However, the later ones were derived just for certain level of relay
antenna height. Validation of the first group to be applicable in relaying environments and expanding the second one for different relay heights is achieved by introducing tuning to the original form of those models.

8.2.1 Tuning of Standard Models

Some well-known examples of standard models are COST231-Hata model and Lee model. In an attempt to make these already coded models applicable in relaying scenarios, some modifications of their original forms are introduced. The modifications are based on an attempt to make these models follow the measurements with small prediction errors and high prediction accuracy for relay heights ranging from 4 to 16 m.

For COST231-Hata model, the adjusted version of the model is given as:

\[
PL_{\text{Adj. COST231–Hata}}[\text{dB}] = A + B \log(d) - \Delta h - 12.47 \tag{8.14}
\]

where the model parameters are given as follows.

\[
A = 46.3 + 33.9 \log(f) - 13.82 \log(h_b) \tag{8.15}
\]

where the frequency \( f \) falls within the 1900 MHz band and \( h_b \) is the transmitter antenna height in meters.
\[ B = 44.9 - 6.55 \log(h_b) \]  \hfill (8.16)

\( \Delta h \) is the relay antenna height correction factor and it is given by:

\[ \Delta h = \left[ 22.21 \log \left( \frac{d}{d_0} \right) + 7.17 \right] \log \left( \frac{h}{4} \right) \]  \hfill (8.17)

It should be noted that \( \Delta h \) is derived from the measurements as it was presented in the previous chapter. Note that the difference between the original COST231-Hata model and the modified version may be explained as follows. The term \( C_m \), in the original form of COST231-Hata model given in (8.4), was omitted since its value is equal to zero for suburban environments. Also the receiver height correction factor \( a \left( h_m \right) \) was replaced by a new one \( \Delta h \). Finally, an adjusting factor of 12.47 dB was added to the modified version of the model.

In the case of Lee model, the modified version is given by:

\[ P_{L_{\text{Adj. Lee}}} = P_{L_0} + m \log \left( \frac{d}{d_0} \right) - H_T - \Delta h - 28.38 \]  \hfill (8.18)

The model parameters are identical to those of the original Lee model given in (8.5) except for the value of \( d_0 \). The reference distance \( (d_0) \) is now equal to 100 meters instead of 1 mile (or 1.609 km). The reference distance is changed since it is quite common to deploy relays at hundreds of meters from the base station. \( \Delta h \) is
defined as in (8.17). Comparing the original form of Lee model and the modified version, one can see that the receive antenna height correction factor has been replaced and a new adjusting factor of 28.38 dB has been added.

8.2.2 Tuning of Existing Relaying Models

Existing relaying models are referred to 3GPP, WINNER B5f and IEEE802.16j models. While the former two models were derived for just one level of relay height, the applicability for the later one was limited to relay heights not to be exceeded 10 meters. Expanding of those models to be applicable for multiple relay heights is proposed in this section. The expansion is accomplished by introducing the relay antenna height correction factor $\Delta h$ which was derived in the previous chapter.

The modified version of 3GPP model is now given as:

$$PL_{Adj.\ 3GPP} = PL_{3GPP} - \Delta h + 0.92$$

(8.19)

where $PL_{3GPP}$ is the predicted path loss calculated by the original 3GPP model, $\Delta h$ is defined as in (8.17), and the adjusting factor 0.92 is the average prediction error ($\mu$) that was provided in Table 8.2.

In the case of WINNER B5f model, the modified version is given by:
\[ PL_{Adj.\ WINNER} = PL_{WINNER} - \Delta h_W - 10.38 \]  \hspace{1cm} (8.20)

where \( PL_{WINNER} \) is the path loss prediction made by the original WINNER B5f model, \( \Delta h_W \) is relay height correction factor, and the adjusting factor 10.38 is the average prediction error (\( \mu \)) that was provided in Table 8.2. Note that \( \Delta h_W \) is slightly different than \( \Delta h \) for other models, and it is defined as:

\[
\Delta h_W = \left[ 22.21 \log\left( \frac{d}{d_0} \right) + 7.17 \right] \log\left( \frac{h}{16} \right) \hspace{1cm} (8.21)
\]

The difference between \( \Delta h \) and \( \Delta h_W \) is that the reference relay antenna height is 4 m for the former one, see (8.17), while for the later one is 16 m, see (8.21).

It is noteworthy to point out that the modified versions of 3GPP and WINNER B5f models are developed by just adding the appropriate adjusting and relay antenna height correction factors to the original forms.

Finally, for IEEE802.16j model, it should be noticed that the applicable range of the receive antenna height was limited to 10 m. The associated receive antenna height correction factor for IEEE802.16j model is modified so that the model can be used to predict the path loss in relay scenarios even when \( h \) greater than 10 m. The modified version of IEEE802.16j model is now given by:
\[ P_{L_{\text{Adj., IEEE}}} = A + 10\gamma \log\left(\frac{d}{d_0}\right) + \Delta P_L - \Delta h_{\text{IEEE}} \] (8.22)

where the modified-model parameters are the same as for the original one except for \( A \) and \( \Delta h_{\text{IEEE}} \) which are defined as follows.

\[ A = 20\log\left(\frac{4\pi d_0}{\lambda}\right) \] (8.23)

and

\[ \Delta h_{\text{IEEE}} = \Delta h_4 + \Delta h \] (8.24)

where \( \Delta h \) is defined as in (8.17) and \( \Delta h_4 \), the correction factor when \( h=4 \) m is given as:

\[ \Delta h_4 = \left[ 6.5\log\left(\frac{d}{d_0}\right) - 9.3 \right] \] (8.25)

Unlike other models, the new factor \( \Delta h_4 \) was necessary in IEEE802.16j model because its prediction is incoherent with the measurements. As was mentioned earlier, the incoherence is attributed to the fact that IEEE802.16j model has large slope (\( m=45 \) dB/decade) compared to the measurements and other models (\( m= 36-38 \) dB/decade). For this reason, \( \Delta h_4 \) is added along with \( \Delta h \) to the original form of
IEEE802.16j model to adjust its slope and make the model prediction follow the measurements.

8.3 Performance Analysis of Tuned Models

The introduction of the correction factors to the existing models achieves two main goals. Firstly, 3GPP, WINNER B5f and IEEE802.16j models are now applicable for multiple relay heights. Additionally, COS231-Hata and Lee models are now expanded into relaying propagation scenarios.

Table 8.3 provides the final comparison between the extended versions of the considered models and the measurements. The comparison is made in terms of the mean ($\mu$) and the standard deviation ($\sigma$) of the prediction error. Table 8.3 clearly shows that the path loss predictions of all discussed models correspond with the measurements, on the average. For all models, $\mu$ is smaller than 0.94 dB, on the average. Note that $\sigma$ represents model's accuracy and it ranges from 2.23 dB for higher relay heights (~16 m) to 6.74 dB for smaller ones (~4 m). These statistical data are in a good agreement with the results obtained from the measurements and presented in the previous chapter. Note that $\sigma$ is getting smaller as the relay antenna becomes higher. This is because the path loss variations (shadowing effects) decrease as the link between the transmitter and the receiver becomes clearer.

Based on Table 8.3, it may be concluded that it is possible to make all considered models perform adequately in relaying scenarios and with approximately
the same accuracy. The modified models can be used to predict the path loss in the backhaul link of relaying systems in 1900 MHz band for distances up to 4 km and within environment similar to the one in which the measurements were conducted.

**Table 8.3**: Comparison between measurements and tuned-models' predictions

<table>
<thead>
<tr>
<th>Model</th>
<th>Metric [dB]</th>
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Chapter 9: Conclusions and Future Work

9.1 Summary and Conclusions

This dissertation presented and analyzed the results of a path loss measurement campaign conducted in a typical suburban environment. The campaign was set up specifically to evaluate the path loss in the relay environment. The measurements are collected in 1900MHz band which is one of the principal bands for the deployment of the LTE and LTE-Advanced. The study is conducted using four different relay heights \( h \) ranging from 4 to 16 m, which are typical heights where one would find relay deployment in various scenarios. Additionally, measurements were conducted at street level antenna height \( h=1.7 \) m.

The work presented in this dissertation achieved two major contributions. Firstly, empirical propagation models for relay environment were proposed and their statistical analysis were provided. Secondly, a relationship between measurements and some existing propagation models was established and suitable correction factors were derived.

Regarding the first contribution, it was found that the path loss may be modeled successfully with a slightly modified log-distance propagation model. The
empirical path loss models for different relay heights presented in this dissertation were derived from the collected data. The parameters associated with the developed empirical models include the slope \((m)\) and the intercept \((PL_0)\) for each level of the examined relay heights. The parameters were determined from empirical studies and through the appropriate linear regression process.

Two different approaches of developing empirical propagation path loss models for relay environment has been achieved. The first one is with fixed environmentally dependent slopes and intercepts. In this approach, the relay antenna height is included in the path loss modeling. Therefore, a general empirical propagation model which takes into account the effect of relay antenna height was derived by introducing a distance dependent antenna height correction factor \((\Delta h)\). The second approach does not include the relay antenna height correction factor but the height of the relay antenna becomes part of the slope and intercept calculation. For both approaches, the analysis results indicate that model predictions are in good agreement with the measurement.

As far as the second contribution of this work is concerned, it started with the performance evaluation of some existing propagation models. Five propagation models namely, 3GPP, WINNER B5f, IEEE802.16j, COST231-Hata and Lee model have been investigated. The validity of existing propagation models is examined by comparing their path loss predictions to the measurements. The
results of the analysis reveal that the applicability of commonly advocated models for relaying environment is still questionable. Therefore, appropriate correction factors were added to their original forms to make all these models perform adequately. With the proposed correction factors, the analyzed models showed good agreement with measurements. Furthermore, it is concluded that with proper correction factors, all the examined models perform adequately and with approximately the same accuracy.

As a final comment, the proposed empirical models as well as the modified versions of existing models might be used to predict the path loss at any particular distance in the backhaul link of relaying systems operating in 1900 MHz band. The models are valid for any given relay station antenna height between 4 m and 16 m and within environment similar to one surveyed in the measurement campaign presented in this dissertation.

### 9.2 Future Work

The presented work in this dissertation proposed some models that might be used to predict path loss in relaying environments. Additionally, the measurements were carried out in a certain environment. As it is known, path loss models perform differently as the environment changes. Furthermore, the measurements were conducted in 1900 MHz frequency band only. In practice, however, loss is almost
always frequency dependent. Therefore, straightforward extensions of this work might include the following:

- Evaluation of the proposed models performance in different environments like urban, dense urban or rural areas and consequently derivation of the appropriate environmentally dependent correction factors.
- Conducting measurements at different frequency bands and consequently derivation of the appropriate frequency dependent correction factor.
## Appendix: Antenna Pattern Data

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