ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Comparison and Fine Tuning Empirical Pathloss Models at 1800MHZ and 2100MHZ Bands for Addis Ababa, Ethiopia

By

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Advisor

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Declaration

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

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Place: Addis Ababa

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

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Abstract

Pathloss models play a very important role in wireless communications in coverage planning, interference estimations, frequency assignments, Location Based Services (LBS), etc. They are used to estimate the average pathloss a signal experience at a particular distance from a transmitter. Inaccurate propagation models may result in poor coverage, poor quality of service or high investment cost. Both second generation (2G) and third generation (3G) networks in the city of Addis Ababa (AA), Ethiopia, have problems like poor coverage, low data throughput, call drops and others. One of the root causes of these problems is the use of untuned pathloss model during network planning. So, it is mandatory for the operators to select the best fit pathloss model and tune it according to the specific situation the pathloss model is used. This thesis compares three pathloss models; namely, COST231, ECC-33 and SUI and tunes the one that performs best in the specific area type.

At 1800MHZ band, COST231 was best in estimating the measured path loss in urban areas with a Root Mean Squared Error (RMSE) of 3.27dB before tuning and the RMSE could improve to 3.25dB after tuning. COST231 was also best in suburban areas with an RMSE of 5.27dB. Tuning the model could improve the RMSE to 4.18dB. SUI was best in open areas. It has an RMSE value of 6.0dB before tuning. Tuning has improved the RMSE value to 4.91dB.

At 2100MHZ, 25 sites are used to collect path loss data. Similar analysis was done in the three path loss models. Based on the analysis, SUI is found to be best in predicting the path loss for all the three morphology types. Although ECC-33 was equally competent for urban area sites, SUI could predict the path loss better for the overall all average measured path loss with an RMSE of 4.27dB. Tuning the model could improve the RMSE to 2.23dB. The measured path loss for suburban areas could also be better predicted by SUI with an RMSE value of 5.75dB before tuning and 2.57dB after tuning. Path loss in open areas can also be better predicted by SUI. It has an RMSE value of 6.53dB before tuning. An improvement in RMSE to 3.38dB could be achieved after tuning.

Keywords — Path loss, tuning, prediction, modelling, error, urban, suburban, open.

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List of Acronyms

AA	Addis Ababa
COST	Cooperation for Science and Technology
DT	Drive Test
ECC	European Communication Committee
GSM	Global System for Mobile Communication
HF	High Frequency
HO	Hand Over
LLSM	Linear Least Square Method
LOS	Line of Sight
MAPE	Mean Absolute Percentage Error
ME	Mean Error
MHZ	Mega Hertz
MSC	Mobile Switching Center
NLOS	None Line of Sight
PSTN	Public Switched Telephone Network
RMSE	Root Mean Squared Error
SD	Standard Deviation
SUI	Stanford University Interim
TCO	Total Cost of Ownership
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunication System
VHF	Very High Frequency

1. Introduction

Cities are more susceptible to bad network coverage. One of the main reasons is due to the use of inaccurate inputs for network planning [19,p.102]. Coverage planning is one of the core planning activities when dimensioning cellular networks. The main input to the coverage planning is a propagation model. Path loss models enable us to estimate the path loss at a particular distance from the base station. Path loss is the phenomenon which occurs when the received signal becomes weaker and weaker due to increasing distance and interfering objects between transmitting and receiving stations. Path loss is also influenced by terrain contours, environment (urban or rural, vegetation and foliage), propagation medium (dry or moist air), and the height and location of antennas [1]. It is difficult to estimate radio signal losses through such uncertain environmental conditions.

Thus, accurate path loss models are required to estimate the signal strength in the radio environment of the cellular network for better quality of signal, coverage area, interference analysis, frequency assignments and cell parameters which are basic elements for network planning process in mobile radio systems [1]. Path loss models are applied in a feasibility studies, new network deployments, optimizing the networks and interference studies through determining the characteristics of the radio propagation channel. The path loss models needs to be tested to check their performance against a measured data and fine-tuned to obtain the best values of the variables that can best reflect the characteristics of the radio propagation channel in the environment the model is used [2][3].

Cities have the most changing environment due to a fast growing of high rising and highly dense buildings. We can also observe that cities have different environment types (i.e. morphology types) across its region. Hence, propagation models tuned to each environment type should be considered when planning cellular networks. Mostly propagation models have variants in accordance with the morphology types.

Empirical path loss models can't fit the environment as they are in their original form. So, measurements have to be done and rigorous mathematical technics are used to fine-tune the models. Although the network is designed to have full coverage in the city, that is not the actual case. Coverage problems are issues in Addis Ababa that demand daily focus. It is not that difficult to get witnesses for this problem among even any passersby in a road. This problem is due to the fact that the coverage planning is not done with the right path loss model as an input. To the best of my knowledge, there is no tuned model used by ethio telecom. It would at least need a tuned model for the current environment. ethio telecom would benefit from using the tuned model. The benefit could be either in saving of an investment cost or in delivering quality of service. This can be demonstrated with the following. There are 710 sites in Addis Ababa (AA) and if they had been designed to cover an area less than they should (e.g. 50m radius for 700m radius site), this would result in extra investment for an area equal to 150 sq.km. This is equal to roughly 114 sites. We can imagine the quality problems if the sites happened to cover areas greater than they should.

Hence, this thesis focuses on selecting the right propagation model and fine tuning based on the measurement data taken from various sites in different areas of AA.

1.1. Statement of the Problem

Coverage planning is one of the major tasks in network dimensioning. Propagation model is the main input to the coverage planning task. COST 231 is used by ethio telecom to make coverage planning for GSM and WCDMA networks in AA. But the model was not fine-tuned for the specific situation of AA. There are coverage problems, poor quality of service and poor quality of experience in both GSM and WCDMA networks. The root cause of these problems could be of diverse nature but one contributing factor is also lack of using a well fine-tuned COST 231 propagation model (or a known tuning parameters)/well-suited path loss model. Propagation models are known to depend mainly on the environment the signal is propagating in additional to others factors. So they have to reflect the actual effect of the environment. Since ethio telecom will have network deployments both in AA and major towns of the country, it is required to get best-fitted and fine-tuned model for better dimensioning of the network. This can as well save investment cost in addition to solving the problems stated above. So, this thesis aims to compare three propagation models (COST 231, SUI and ECC-33), select the best performing one in the specific environment and at 1800 and 2100 MHZ and fine-tune for best compliance of the environment through actual field data measurements.

1.2. Objective

1.2.1. General Objective

The main objective of this thesis is to compare COST 231, SUI and ECC-33 for different environments of AA at 1800 and 2100 MHZ bands and fine-tune the parameters that model the environment based on measurements.

1.2.2. Specific Objectives

The following specific objectives will be achieved during the course of this thesis:

- Identify potential propagation models for 1800 and 2100 MHZ cellular network.
- Measure the signal strength at different distances from the transmitter and calculate the actual path loss.
- Calculate the errors Root Mean Square Error (RMSE), Mean Error (ME), Standard Deviation (SD), and Mean Absolute Percentage Error (MAPE) and evaluate the performance of the three models, COST231, SUI and ECC-33.
- Identify the possible morphology type (i.e. Urban, Suburban and Open) of each measured site
- Fine-tune the models on their specific morphology type and evaluate their performance.
- Propose one model with the good values of the tuning parameters that fits best for the particular area.

1.3. Scope and Limitation of the thesis

1.3.1. Scope

This thesis work will analyze only three propagation models (COST231, SUI and ECC-33) among other propagation models that can be applied for cellular network [4]. The field data measurement is also limited to AA and hence, the result can also be mostly applied to the areas of AA and of course for areas of similar nature. The study considers also only two carrier frequencies, 1800 and 2100MHZ for which GSM and UMTS are used respectively for field data measurements.

1.3.2. Limitation

The limitations of the thesis are mostly observed during the field data measurements and taking parameters of the sites to manipulate the path loss. Measurements were taken by different tools (i.e. Nemo Outdoor and Nemo Handy) which may result in slightly different measurements for the same point due to different sensitivity of the tools. Since the measurement is taken from the operational base stations of GSM and UMTS networks (i.e., not a standalone antenna), the area of measurement is bounded to the sector. This will cause wrong measurements as the driving ways sometimes lead to out of the sector coverage. The carrier frequency of the sites is widely varying specially for GSM but only 1800MHZ is used for manipulation of the path loss for the propagation models. Antenna heights, Azimuth angle, Vertical angle and transmit power may vary from site to site but a single representative values are used for simplicity of the process.

1.4. Literature Review

Experiment was done in Mumbai, India, in dense urban, urban and open areas [5]. A linear-iterative tuning method using least square theory is used to tune COST-231 Hata propagation model. Mean errors (ME), error's standard deviation (SD), root mean square error and coefficient of determination of tuned model are used to compare the measured data with the classical COST-231 Hata. A reduction up to 14.3 dB, 3.5 dB and 14.4 dB of ME, SD and RMSE respectively was achieved in the tuned model and 90% for coefficient of determination of tuned model (a measure of how well the fitted curve represents the data). The authors concluded that the result (i.e. the tuned model) can be used to predict the signal and path losses in the whole area of Mumbai. The paper didn't consider other propagation models.

Performance evaluation of empirical propagation models was presented on [6]. Field data measurements were carried out at various distances from the WCDMA base station at a frequency of 2100MHZ. The test was carried out on three different locations in Rivers State, Nigeria. Different path loss measurements were taken at various distances from the base station and comparison was done based on root mean square error (MSE) and standard deviation (SD) between the measured path loss and predictions by ECC-33, SUI, COST 231 Hata models. An MSE value of 14 , 17 and 20 dB was calculated for COST 231 empirical model for Rural, Suburban and Urban, an MSE of 36,36,37 dB for SUI for Rural, Suburban and Urban areas and an MSE of 118, 169 and 162 dB for ECC-33 for Rural, Suburban and Urban areas respectively. Although all MSE are far beyond the acceptable values, COST 231 has shown better agreement with the measured data. An adjustment was also done to further increase the accuracy of COST 231 and an MSE of 3.16, 0.124 and 0.123 dB could be achieved for respectively of Urban, Suburban and Rural areas. The paper has considered three propagations models and also considered three morphology types but took measurement data only from three locations at only 2100 MHZ.

Three propagation models were compared in [7] in Sofia. COST 231 has shown lower RMSE among the other two propagation models, i.e., Ericsson and Log-distance. The paper further states that the RMSE of all the models after tuning is 11.8dBm. It is very skeptical that the RMSE of all the models after tuning is the same. It considers only 1800 MHZ. Similarly, COST 231 is also shown to have better accuracy than ECC-33 model and SUI model based on the measured field path loss values taken in Hyderaband, India. The model was further fine-tuned using least square algorithm. The tuned model gives a mean error of 1.294, root mean square error of 4.764, standard deviation of 4.29 and a relative error of 12.75% [8]. Only five sites were considered. This may bias the results obtained.

In [9], Free space model, SUI, ECC-33 and COST231 were studied at Ghaziabad, India at 1.8 GHZ. Five base stations were selected for measurement in dense Urban using the GSM network and linear iterative tuning process were employed. Here also COST 231 was proved to score a minimum RMSE. A minimum of 7.99 and maximum of 14.27 RMSE was calculated for COST 231 for the five measured sites. The seasonal variation of the measurement was considered better than other studies as the measurement period was six months but other frequency ranges and morphology types are not included in this work. Another study conducted in Owerri, Nigeria has also concluded that COST 231 has better agreement with the measured data than other propagation models such as Okumura-Hata and Egli. The authors studied only 2100MHZ at Urban areas and the conclusion was made by taking measuremnt only from four base station.

Although COST 231 was champion in all the studies presented above, Studies in [10][11][12][13] has shown that SUI could represent the measured data better than COST 231, Ericsson, Log-normal shadowing, Lee model, ,Egli model and ECC-33 at 1.8GHZ, 1.9GHZ and 2.6GHZ in Suburban and Rular areas in Bandar Seri Iskandar and Kuala Lumpur, Malaysia and. ECC-33 showed the best result among COST 231 and SUI in Cambridge, UK in Urban areas at 3.5GHZ for a measurement taken in Fixed Wireless Networks [3][14]. Hence we can't conclude that a particular propagation model is best for all the environment types and for all frequency ranges. Different propagation models can be best for the same area with varying morphology types and frequency ranges as depicted in [15][16]. Hence, it is not possible to guarantee a single propagation model for the city of AA unless and otherwise researches such as this one confirms which can best fit for the environment of AA based on its morphology types and changes occuring with time in the City.

1.5. Methodology

A survey of empirical propagation models was carried out to identify the propagation models potential to 1800 and 2100 MHZ bands. Locations to take field data measurements was decided in a way which can represent the morphology type and terrain profile of AA. A high number of data was collected to compare the actual measured pathloss with the pathloss calculated from empirical models using different error measuring tools such as RMSE, Mean Error (ME), Standard Deviation (SD) and Mean Absolute Percentage Error (MAPE). Data is collected by the drive test using tools such as labtop, mobile terminals, Nemo software (Licensed) and GPS. Matlab was also used to simulate both the measured and empirical model path losses. Then errors were minimized through tuning of the models using least squared error. This has brought a tuned model that fits for the target environment. Finally, the results were evaluated to give definition of demarcation for morphology types.

1.6. Contribution of the Thesis

To the best of my knowledge and other ethio telecom planning experts, ethio telecom uses the empirical COST 231 propagation model as an input to its planning and optimization process for its previous network dimensioning programs. COST 231 tuning was done a couple of years ago by Orange (a foreign company who contracted the company's management) but results were never exposed to ethio telecom. So, this thesis has the following contributions:

- I have contributed in filling the knowledge gap in selection of best predicting pathloss model and tuning techniques for the pathloss model to fit for the environment in focus.
- I can as well trigger other researchers or even ethio telecom staffs to further study and even include frequency ranges and areas not covered by this study as such studies are required in an ongoing basis due to environmental changes.

1.7. Thesis Layout

This thesis work is structured in the following way. Chapter one is an introduction chapter in which objectives, Problem statment, Literature review and contribution are included. It gives a general over view of the research. Basics of propagation, small scale effects and large scale effects and fading channels are described in Chapter two. Chapter three is dedicated for over view of propagation models used for cellular networks. It also includes in depth the properties of the propagation models with variation of their parameters such as frequency, heights and distances. Details about measurement procedures, measurement challenges, measurement tools and selection of sites are explained in Chapter four. Chapter five and chapter six present the data analysis and results of the analysis.

2. Cellular Network Coverage Planning

Path loss model has wide application in wireless environments. A radio signal of any type from the transmitter has to be estimated what signal strength the radio signal has at a particular point. This should be determined to identify whether the receiver is able to decode the information sent. Based on the feedback from the receiver, adjustments can be done. The adjustments could be increasing transmitter power, increasing receiver sensitivity, decreasing distance between transmitter and receiver, etc. So estimating the signal strength at any point at a given environment with given parameters such as frequency, antenna heights, etc, is crucial for the success of wireless communication. The estimation is effected through path loss models. These models are of various types based on their applications. They can be applied in Satellite communication, Cellular communication, Broadcast communication, Wireless point to point communications, etc. The coverage planning of all these networks are supported through estimation of the signal strength using the path loss models. Cellular network coverage planning is one key application of path loss models. Not only in Coverage planning, path loss models are also necessary in cellular networks for interference estimations, frequency assignments, and location based services (LBS) which are not based on Global Positioning System (GPS) [22]. Path loss models determine the number of base stations in a particular area. If a wrong coverage estimate is used (i.e. wrong path loss model), there will be either coverage problem or interference. This may lead to high cost of investment and customer dissatisfaction. Hence the right path loss model representing the current environment should be sought to have a proper coverage planning in cellular networks. Here in this chapter I will describe the path loss models in cellular network planning.

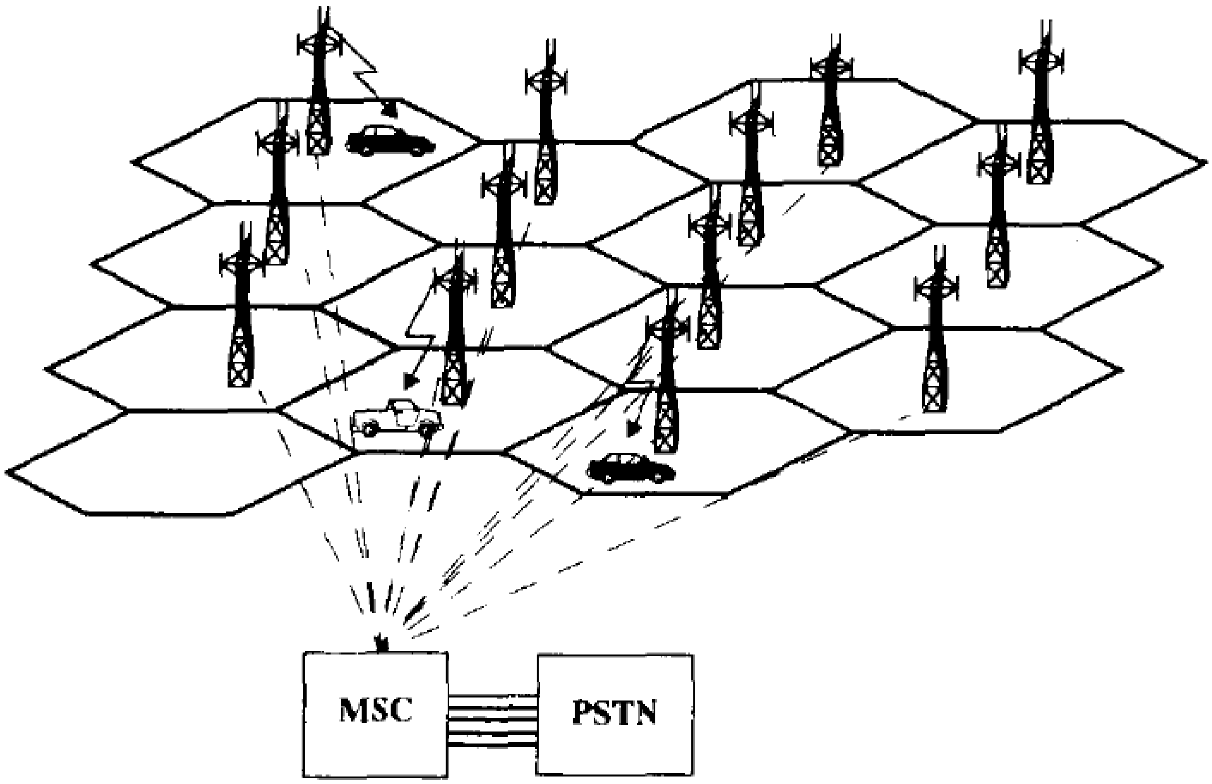


Figure 1 Cellular Networks [19]

2.1. Cellular Network Coverage Planning processes

Mobile communication has vital role in our daily life. The fast growing mobile technology is enabling us to use it beyond voice application. Data usage, Location applications, financial transactions and many others are emerging in the new mobile communication technology [23]. All these applications are possible if and only if the mobile network is properly designed, implemented and managed. The two key activities in designing a mobile network are capacity planning and coverage planning. The main objective of planning is to minimize Total Cost of Ownership (TCO), maximize capacity, maximize coverage, minimize power consumption and optimize Handover (HO) zones while achieving the maximum quality of service. The planning work is done in three phases: Preplanning (Dimensioning), Detail Planning and Post Planning

(Optimization) [25]. The main output of dimensioning is to estimate the number of base stations required to cover the required area. The locations and better estimation in the number of base stations are determined in the detailed planning. Detailed planning is further explained in the next paragraph. Once the network is deployed and running, adjustments are made in the optimization phase.

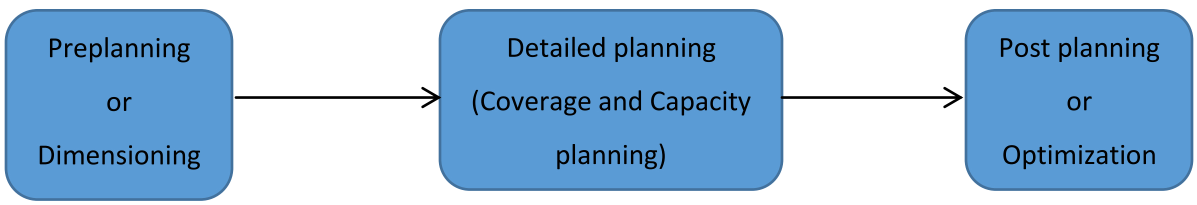


Figure 2 The three phases of planning cellular networks [24]

The following steps are followed in detailed planning of cellular networks: Capacity Planning, Coverage Planning and Parameter Planning [23][24]. The practical processes followed in capacity and coverage planning in different technologies are shown in [24] and also depicted below for further elucidation.

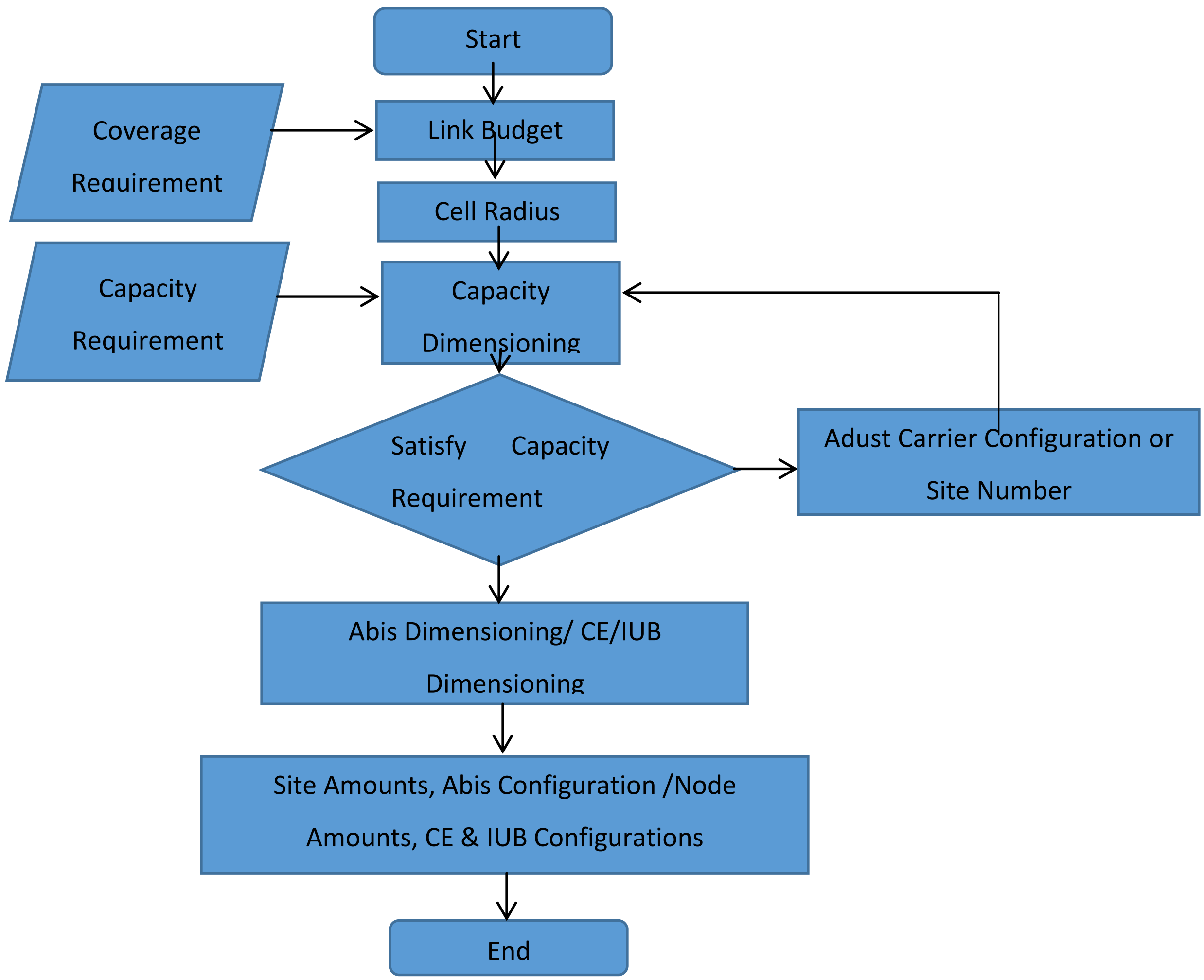


Figure 3 GSM and UMTS Planning Process [24]

As shown in the planning process above, link budget is done with the coverage requirement as an input. The coverage requirement is stated as the coverage probability of, for example, 95% which is the total area the radio signal should cover with acceptable signal strength. Link budget is performed to get the cell radius and the distance between sites. The link budget in any cellular technologies is calculated with the formula below. The value of P_{rx} is highly dependent on the value of Ptx and PL. P_{tx} is obtained by measuring the transmitter output signal strength whereas the value of PL is determined with only a best estimation through path loss models. The value of PL at a point obtained from one path loss model is different from the one obtained from the other. This will vary the value of the received signal (P_{rx}) which will lead to a conclusion that a point which is actually in the acceptable signal strength range to be considered as out of the range or a point which is not actually in the acceptable signal strength range to be considered as in the range. This will either reduce the coverage area of the base station or enlarge the coverage area of the base station beyond the actual one, leading to either incurring higher cost or bad quality of service. so which model to use and what fine-tuned parameters to insert in the models is the next question to be answered. The next paragraph will give some highlights on path loss models.

$$P_{rx} = P_{tx} + G_{Tx} + G_{rx} - L_{tx} - L_{rs} - PL \quad (3)$$

Where,

- Prx - the received power (dBm).
- Ptx - the transmitter output power (dBm).
- Gtx - the transmitter antenna gain (dBi).
- Ltx - cable loss and other loss in transmitter.
- Lrx - Losses in receiver side.
- PL - Path Loss

2.2. Pathloss Models Review

Path loss is the attenuation of the radio signal as it travels from the transmitter to receiver in a particular environment. It could be due to different effects such as refraction, reflection, diffraction, free space loss, coupling loss and absorption [25][26]. It is calculated by subtracting the transmitted power to the received power as shown in the equation below.

$$PL = P_{tx} - P_{rx} \quad (4)$$

The transmitted power is known from the design parameter or by measuring the power output of the transmitter. The received power should be known at a particular point within the supposed coverage area of the base station but not possible to determine as there is a different environmental conditions between the transmitter and the point in attention. Path loss models fill this gap. Path loss models are mathematical expressions of variables such as distance, antenna heights, environmental conditions parameters, frequency, etc that will predict the path loss of a radio signal at a particular distance from the transmitter. There are three categories of path loss models: Empirical models, Semi-empirical models and Deterministic models. The categorization is based on the way they are derived. Some are derived from experiment with data obtained from measurement and some others are derived theoretically from physics principles of radio waves [27]. Still others are of hybrid nature and they are called Semi-empirical.

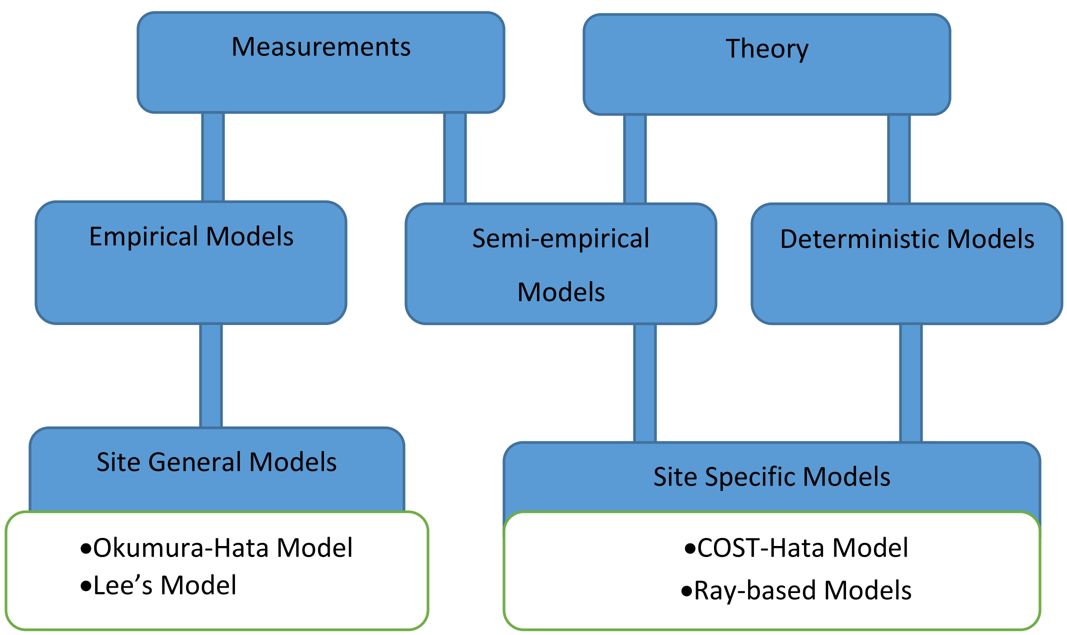


Figure 4 Categories of Pathloss Models [27]

2.2.1. Empirical Models

These models use a set of equations obtained from field data measurement and observation. The data taken should be sufficient enough to include the entire situation in the specified environment. These models have often more practical applications than deterministic models because they don't require site specific information. They are less accurate than deterministic models. They relieve the users of the models from knowing detail information about the environment such as building heights, density of buildings, terrain status, etc which are often very difficult (if not impossible) to get. Rather they use more of system design parameters as frequency, antenna heights, distance between transmitter and receiver, path loss exponents etc which are relatively easier to obtain [27]. Empirical path loss models are subdivided into non time dispersive and time dispersive. Time dispersive models are designed to provide information relating to the time dispersive characteristics of the channel i.e., the multipath delay spread of the channel whereas non time dispersive models predicts mean path loss from the function as distance, antenna height, and so on [3]. SUI is a best example of time dispersive and Okumura and Hata models are examples for non-time dispersive.

2.2.2. Semi-empirical Models

Semi-empirical models use approaches from both deterministic models and empirical models to calculate the path loss. The models are triggered due to the fact that now a day digital terrain data is available. The digital terrain data contains information like terrain heights, land use information and building data. They general make use of low resolution geographic data. The remaining part of the models is compensated by field data measurements like the empirical models. Semi-empirical models give good predictions for macro cells for outdoor environments even in the Cities but are limited in predicting signal strengths in indoor environments [27]. COST-Hata, Lee microcell model and COST231 are models under this category.

2.2.3. Deterministic Models

Deterministic models need detailed geographical information. The path loss information is dependent on the detail information about the terrain profile, road width, building layout, etc. Propagation mechanisms are made in use in a realistic environment to calculate the path loss. This requires very complicated mathematical calculations and also requires high capacity computers for the analysis. In fact, such models give more accurate path loss estimate than both empirical models and semi-empirical models [27][28]. It can as well be applied in any environments with wide range of frequencies at larger distances. These models are so site specific as they design is based on detailed specific environmental information. Ray tracing model is the best example of deterministic model.

We can still classify path loss models based on their application area as cellular network path loss models, sensor network path loss models, broadcast network path loss models etc. The application of the environment is also used for classification. We classify them as indoor and outdoor models. There are seven major classifications of path loss models and 14 subcategories based on a work done in [29]. The seven major categories are:

- Theoretical/Foundational Models
- Basic Models
- Terrain Models
- Supplementary Models
- Stochastic Fading Models
- Many-Ray Models
- Active Measurement Models

Below is the diagram showing the seven categories and subcategories of the path loss models.

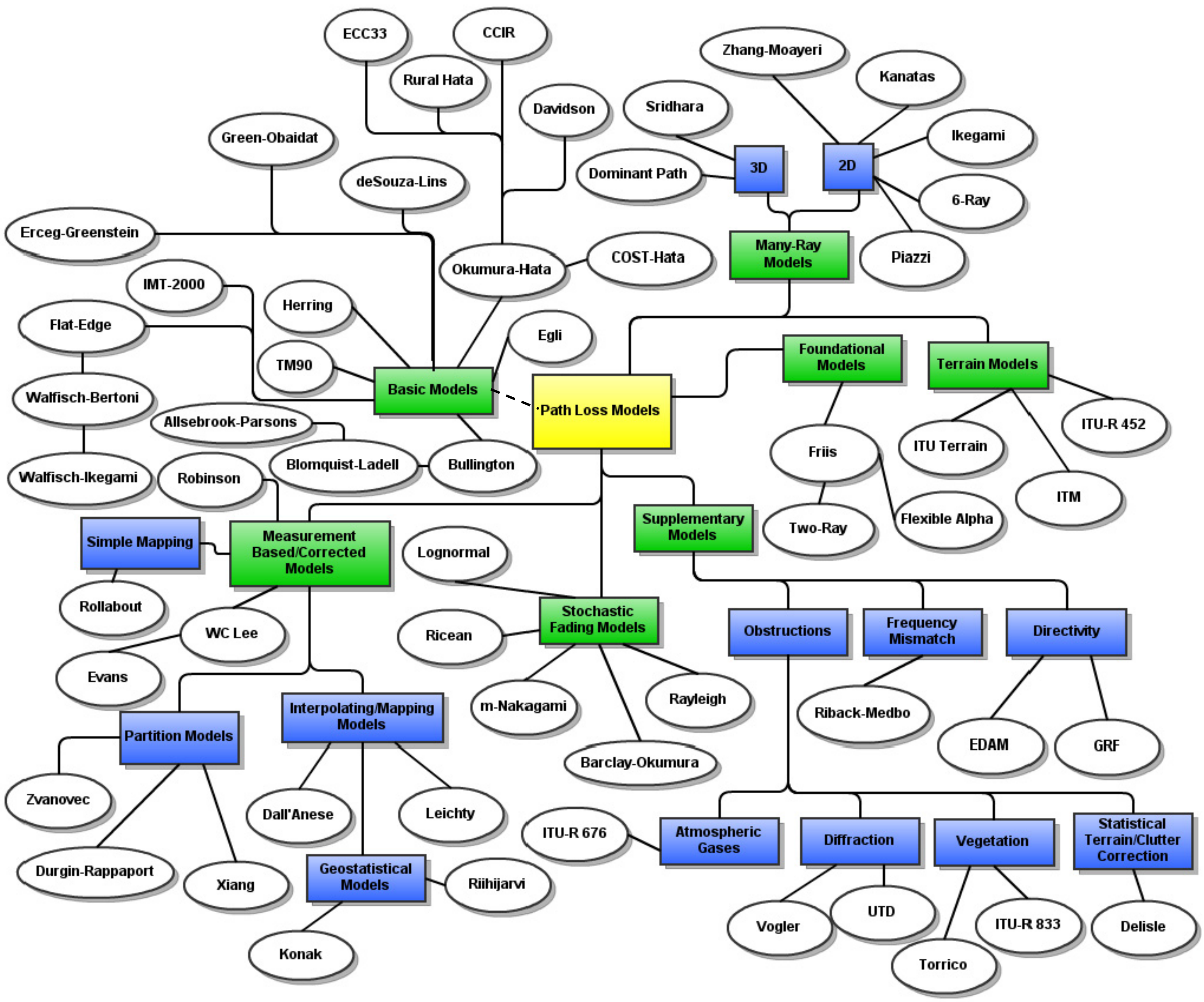


Figure 5 Major and Sub categories of pathloss models [29]

Individual path loss models have also various variants specially based on morphology types. They have Urban, Suburban and Rural models. The use of such models has to be based on the required morphology type.

The selection of path loss model for a particular application should be carefully done. A wrong path loss model for a particular application may result in bad performance or wastage of resources. When we select path loss models, we should first identify the type of network (application) we intend to use the model. Identifying all models that can be used in the specified network will give us a chance to choose the best performing one. Path loss models relevant for a certain network type may differ in their applicability from the perspective of network design parameters such as frequency of operation, distance, antenna heights, etc. So the selection should further be tuned to meet the network design parameters. The selection is not yet over. The environment under which the network is to be deployed should be identified. This will enable us to choose a path loss model most relevant for the environment identified. Urban, Suburban and Rural are the major classes of environment type. Hence the relevant model should be selected. This is mostly for the cases of Empirical models. If Deterministic models are used, then the detail geographic and environmental information should be studied and a relevant model should be designed.

The table below shows the list of path loss models with their Pros and Cons, application environment, frequency range, etc.

Model	Frequency Range	Type of Terrain	Pro	Cons
Okumura's Model	150MHz to 1950MHz	Urban, Suburban & Rural	Best Model for dense cities	Slow response to quick Terrain profile changes and not good in rural areas

Hata Model	150MHz to 1500MHz	Urban, Sub-urban & Rural	Suitable for large cell mobile system	Not so good for rural hilly terrains
Hata-Okumura Model	150MHz to 1.5GHz	Metropolitan areas, small and medium sizedcities, suburban and rural areas	Fairly accurate path loss estimation	Does not model propagation in cellular systems with higher frequencies
Stanford University Interim Model	2.5GHz to 2.7GHz	Hilly and Flat Terrains	Used to estimate the signal strength in all three terrain profiles like urban, suburban and rural.	Does not divide terrain profile into the rural, suburban and urban. This can be additional source of calculation incorrectness
Two ray Ground Reflection Model	Applicable to any Frequency	Plane earth	Useful and Simple model for propagation over long distances	Results are less satisfactory for shorter distances
Longley rice Model	20 MHz to 20GHz	Point to Point communication over Irregular terrains	Path specific parameters can be easily calculated when the detailed terrain profile is available	Does not provide a way of Calculating correction due to environmental factor
COST 231	1500MHz	Urban, Sub-	Suited for predictions	Graphical expressions

Hata Model	to 2GHz	urban and Rural	in microcells given that transmit antennas are above roof top	are not practical
COST 231 Walfisch-Ikegami Model	800MHz to 2000MHz	Flat urban terrain	This model distinguishes between LoS and NLoS	More complex
Ericsson Model	1900MHz	Urban, Sub-urban and Rural	Very fast	Extensive Test measurements are carried out in order to collect the data
Egli	40MHZ – 900MHZ	Irregular Terrain	Suitable for wireless communication where one antenna is fixed and the other is mobile	Not applicable in the area where some vegetative obstruction, such as trees or shrubbery is in the middle of the link
Log-distance	All range of requencies	Wide range of conditions	Used both in LOS and NLOS	Not tuned to certain applications, generic model
Durkin's Model		Irregular terrain	Provides perspective into the nature of propagation	Cannot predict propagation effects due to foliage, buildings, and other manmade structures and doesn't support multi path Communication.
Young's model	150 to 3700 MHz	Large cities with tall structures	Good performance in Urban	Doesn't include other morphology types
Lee Model	> 30MHZ	Flat terrain	Covers all range of frequencies	Has limitations at some values of parameters
ITU Model	900 MHz	Indoor	Has two variants: ITU	Not good for tropical regions

	to 5.2 GHz	environment	Terrestrial model and Crane model	
Ikegami Model	All frequency ranges	All situations	Deterministic and hence more accurate	Underestimation at large distances and slow frequency variation response compared to measurement
ECC-33	Up to 3.5GHZ	Urban, Suburban and Open	Good for Urban areas	Correction factors required for Suburban and Open areas
Log-normal	Independent of frequency	In all situations	Good for wireless sensor networks	Does not consider temporal variation
Perez-Vega Zamanillo Model	Independent of frequency, used for VHF and UHF communications	Outdoor environment	Simple and applicable in a wide range of distances	Limited to only some ranges of antenna heights (receiving and transmitting)
Green-Obaidat Model	2.4GHZ	Wireless LAN	More accurate	Does not take into account the impact of fading caused by several objects, e.g., building, foliage, etc
Free space pathLoss	Wide range of frequencie	In all situations	Doesn't require much environmental detail	Does not account for multipath propagation and cannot be used for point-multipoint radio

Model (FSPL), aka Friis model	s			link. Requires LOS

Table1 List of path loss models

2.3. Propagation Models for Cellular Network Planning

Among the myriads of the path loss models available in literature, there are only some relevant to the cellular network. These path loss models should address the specific nature of the cellular networks. Cellular networks are characterized by having small areas of cell coverage, repetition in the use of frequency, lots of interference between the base station and mobile station, etc. The path loss in cellular networks is determined by different parameters as height of the base station antenna, height of the mobile station antenna, frequency of operation and the environmental condition & distance between the base station and the mobile station. So the models should comply with the specific operating parameters of the cellular networks. The frequency of operation of cellular networks is from 450MHZ to 2600MHZ. Path loss models operating only in this range should be used for cellular networks. Height of mobile stations is from around 1m to 3m, base station antenna heights are in the range of 10m. Path loss models applicable for cellular network should also consider this. Distance between base station and mobile station range from around 500m to few kilometers depending on traffic and environment of the site. Base stations operate in various environment types such as dense urban where there are high rising buildings, lot of people, many vehicles, etc, suburban and open areas. All this tells us that path loss models (specially empirical and semi-empirical ones) should consider such specific situations of cellular networks. The following are some of the most common empirical and semi-empirical path loss models used in cellular networks.

- ✓COST231 Hata model
- ✓COST231 Walkfisch Ikegami Model

- ✓ECC-33
- ✓SUI
- ✓Egli
- ✓Okumura-Hata
- ✓Ericcson
- ✓Log-Distance
- ✓Etc

Below is the model used in this thesis to analyze the path loss models for cellular networks

Path loss models are used to estimate the signal path loss due to various factors in an environment. The figure below shows the various factors in the environment, the main one being buildings, trees, terrain profile, and distance. The signal transmitted from the base station antenna is distorted and attenuated due to the various environmental factors and received by the mobile station. The environment from the BS to MS can be modeled by the path loss. We can imagine as if the signal is processed through these path loss models. Path loss models should be tuned to represent the environment better.

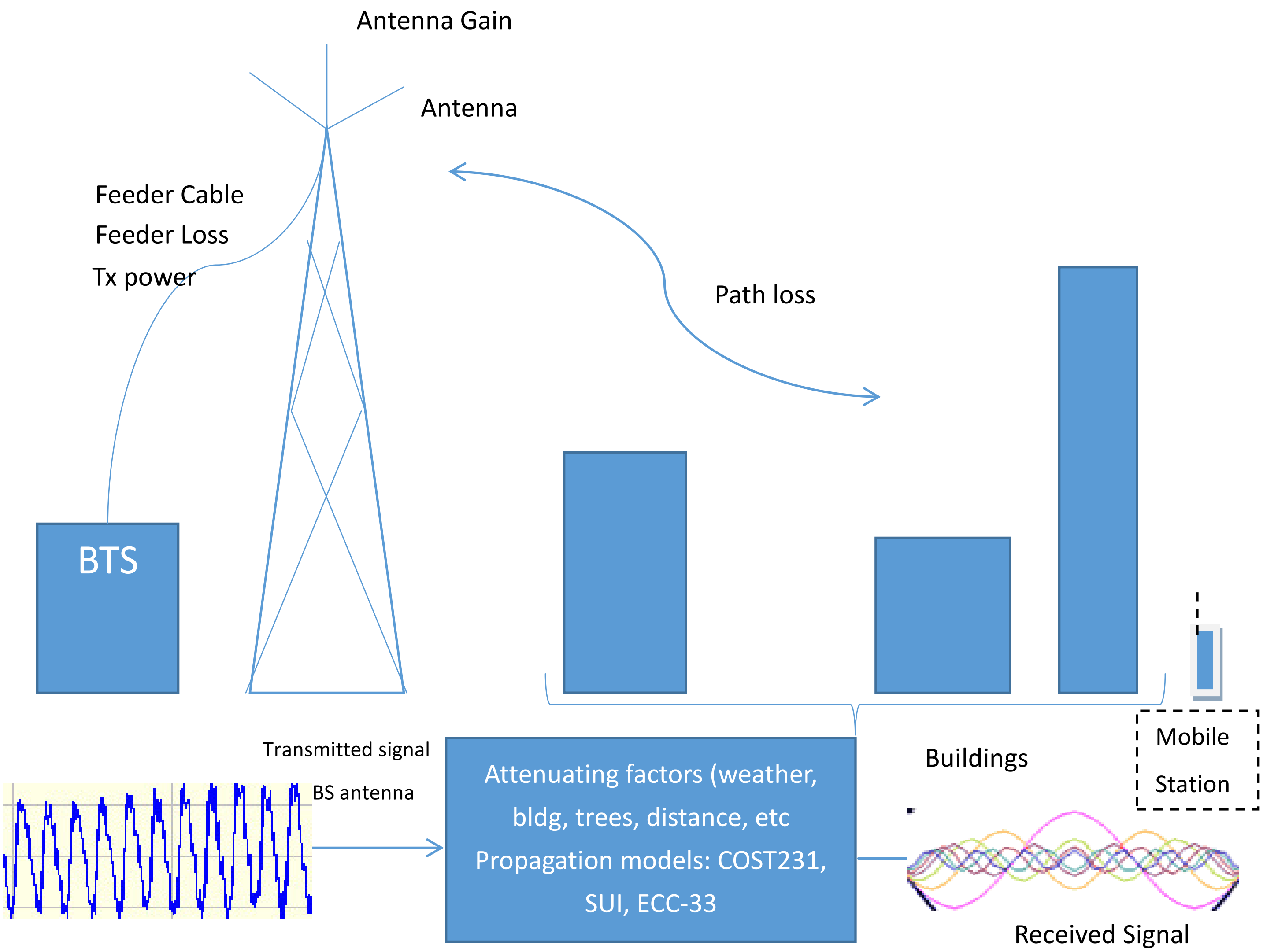


Figure 6 System modelling for path loss models

2.4. Analysis of Propagation Models (COST231, SUI and ECC-33)

Various cellular network path loss models have been analyzed and tuned in different areas at different frequencies[1][2][3][5][6][7]. Selection of the possible path loss models for AA was done according to the following process.

1.Intensive literature review have been done to see what path loss models are available. Very many path loss models are available in literature.

2.Selection of those models relevant for cellular networks

3.Selection of models that are more relevant for AA and for operating frequencies of 1800MHZ and 2100MHZ

According to the above process, three models: COST 231, SUI and ECC-33 were selected to be more relevant for 1800 MHZ and 2100 MHZ in AA. They were selected for the following reasons.

1.They were the most selected models with measurment data in many papers

2.These models were best performing in different cities. For example, SUI has been best in agreeing with the measurement data in Malaysia as per the paper in [11]. According to [3] and [14], ECC-33 has outsmarted other path loss models in India. The study conducted in Hyderaband and Ghaziband, India, showed that COST 231 is the most suitable path loss model [8][9].

3.They are applicable in Cities like AA.

4.They are also applicable at 1800MHZ and 2100MHZ frequencies.

2.4.1. Stanford University Interim (SUI) Model

This standard was developed by Stanford University in 2007 E.C after it is proposed by IEEE 802.16 for the frequency range below 11GHZ [3]. This model has been derived as an extension to Hata model with 1900 MHz frequency band and above [4]. The SUI model is derived for the multipoint microwave distribution system (MMDS) for the frequency range from 2.5 GHZ to 2.7 GHZ [3][18]. The model can support a BS antenna height from 10m – 80m, MS antenna height from 2m to 10m and distance from 100m to 8000m.

This model covers three terrain types. Terrain A, B and C. Terrain A is one that has maximum path loss. This terrain type is hilly with moderate to heavy tree densities. Terrain B is one with mostly flat terrains with moderate to heavy tree densitites or hilly terrains with light tree densities. Path loss is also of moderate value in this type of terrain. The third type of terrain has the least path loss compared to the other two. Terrain C has flat terrain with light tree densities [3][4][18]. Terrain A is taken as an equivalent of Urban area, Terrain B is also taken as an equivalent of Suburban area and Terrain C is taken as rural area [15]

Type C is associated with minimum path loss and applies to flat terrain with light tree densities. Type B is characterised with either mostly flat terrains with moderate to heavy tree densities or hilly terrains with light tree densities.

The basic path loss equation of SUI is given in [10] as

$PL = A + 10\gamma \log_{10}^{(d/d0)} + x_f + x_h + s$ for d > d_0 ---(5)

where, d is the distance between the transmitter and the transmitter's antennas in metres and d > d_0,

d_0 = 100 m and is a reference distance

s is a lognormally distributed factor that is used to account for the shadow fading owing to trees and other clutter and has a value between 8.2 dB and 10.6 dB.

X_f – as a correction for frequencies above 2 GHz in (MHz);

X_h – correction factors for receiving antenna height above 2 meters;

γ – as a path loss component

In the equation [4] above, the parameters A and γ are defined as follows:

A $= 20\log_{10}^{(4\pi d_0/\lambda)}$ --(6)

$\gamma = a - bh_b + c/h_b$ ---(7)

where, the parameter h_b is the base station height above ground in metres and should be between 10 m and 80 m. The values a, b and c in equation 6 depends on the terrain type and is given in table 2 below.

Model parameter	Terrain A	Terrain B	Terrain C
a	4.6	4.0	3.6
b (m^{-1})	0.0075	0.0065	0.005
c (m)	12.6	17.1	20

Table 2 Values of a, b, and c

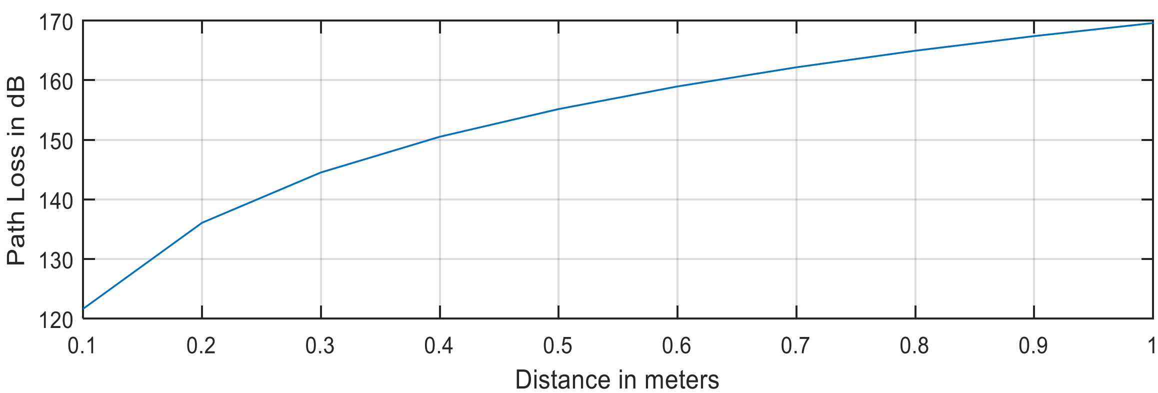
$$x_f = 6.0\log_{10}^{f/2000} \text{ --- (8)}$$

and,

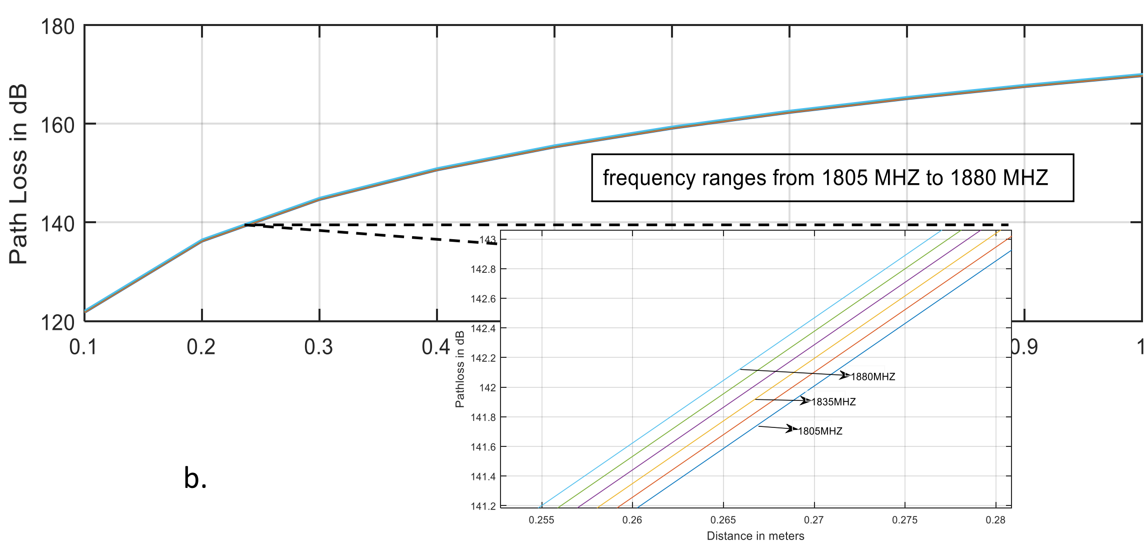
$x_h = -10.8\log_{10}^{(h_r/2000)}$ for Terrain types A and B

$x_h = -20\log_{10}^{(h_r/2000)}$ for Terrain type C ---(9)

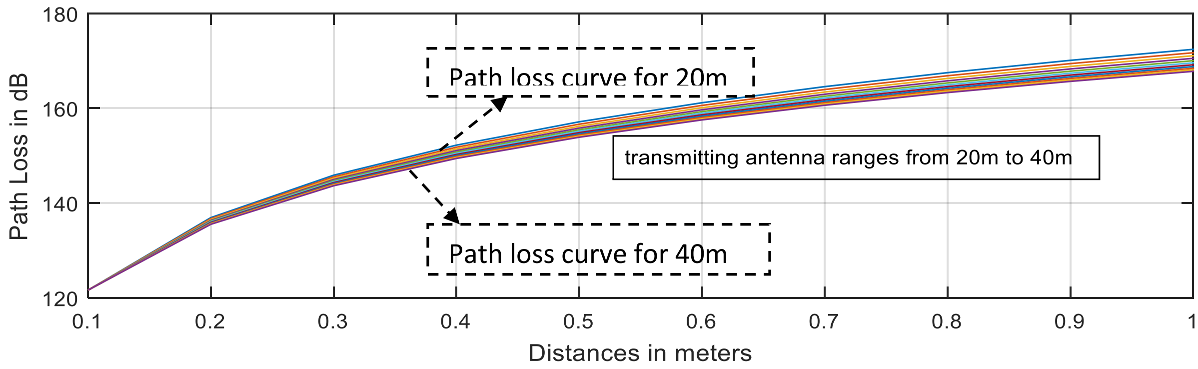
where, f is the frequency in MHz and h_r is the receiving antenna height above ground in metres. The SUI model is used to predict the path loss in all three environments, namely rural suburban and urban. We see from the equation of SUI that the path loss depends on variables as receiving and transmitting antenna heights, frequency of operation, and distance. Let us now see the effect of each variable by fixing the other varibles. Urban model is used for the analysis.



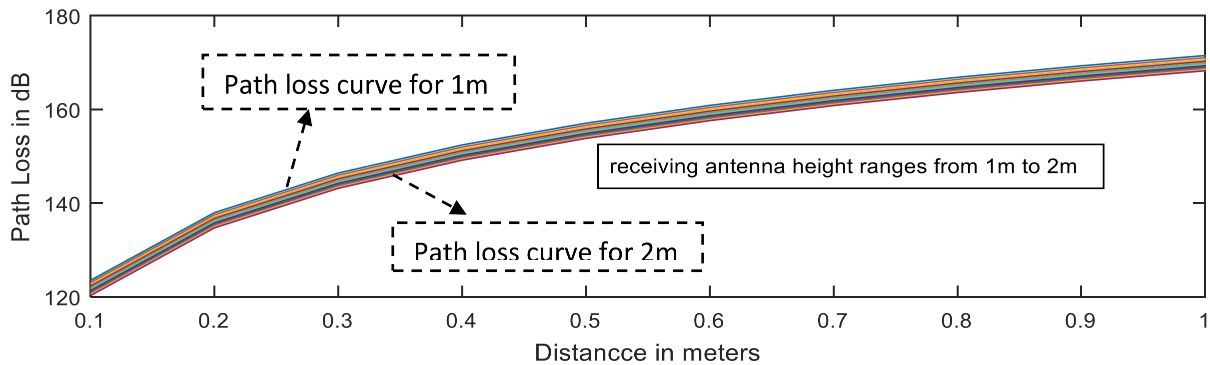
a.



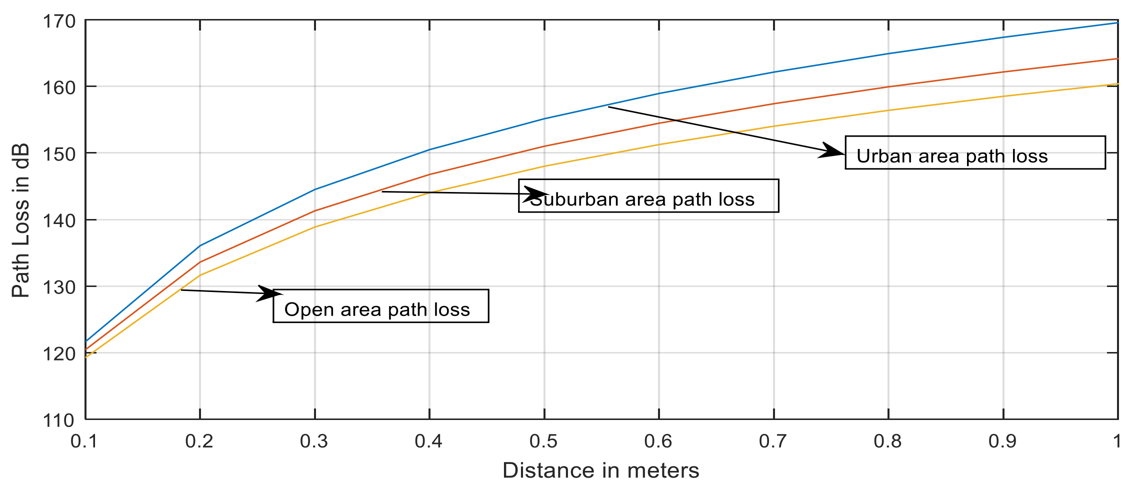
b.



c.



d.



e.

Figure 7 Path loss with SUI model in a. Variation of distance b. Variation of frequency c. Variation of transmitting antenna heights and d. Variation of receiving antenna heights e. Urban, Suburban and Open areas path loss

SUI model has distance as an indepent variable in which case thepath loss increase with distance. This sounds logical as there could be different interefering objects as the separation between the transmitter and receiver is getting increased. As can be seen from fig.7 b, SUI will show variation of only 0.46dB (an increase in the path loss) when the frequency is increasing from 1805 MHZ to 1880 MHZ. An increase in transmitting antenna will result in the decrease of the path loss in SUI. If the antenna height is increased from 20 to 40m keeping all other parameters the same, the path loss difference will increase from 0db to 5.02dB as the distance increases from 100m to 1200m (fig.7 c). A receiving antenna variation from 1m to 2m will cause the path loss to decrease by an amount of 3.25dB regardless of the distance as shown in fig.7d. Obviously, higher antenna height will likely to have less no of interefering objects.

2.4.2. ECC-33

ECC-33 path loss model was originally developed by Electronic Communication Committee (ECC). It is developed by extrapolating the Hata Okummura model, which is questionable in its accuracy in higher frequencies despite its purpose for UHF, and modifying its assumptions [3][8]. ECC-33 can support frequencies greater than 3GHZ unlike Hata Okumura which supports frquencies below 3GHZ. The model can also support a BS antenna height from 10m – 80m, MS antenna height from 2m to 10m and distance from 100m to 8000m.

The path loss in ECC-33 model is defined as,

$$PL = A_{fs} + A_{bm} - G_b - G_r \text{ --(10)}$$

where, A_{fs}, A_{bm}, G_b and G_r are the free space attenuation, the basic median path loss, the base station (BS) antenna height gain factor and the mobile station (MS) antenna height gain factor. They are individually defined as,

$$A_{fs} = 92.4 + 20\log_{10}^{d} + 20\log_{10}^{f} \text{ ---(11)}$$

$$A_{bm} = 20.41 + 9.83\log_{10}^{d} + 7.894\log_{10}^{f} + 9.56[\log_{10}^{f}]^2 \text{ ---(12)}$$

$$G_b = \log_{10}^{(h_b/200)}\{13.958 + 5.8[\log_{10}^{d}]^2\} \text{ --(13)}$$

For medium city environments,

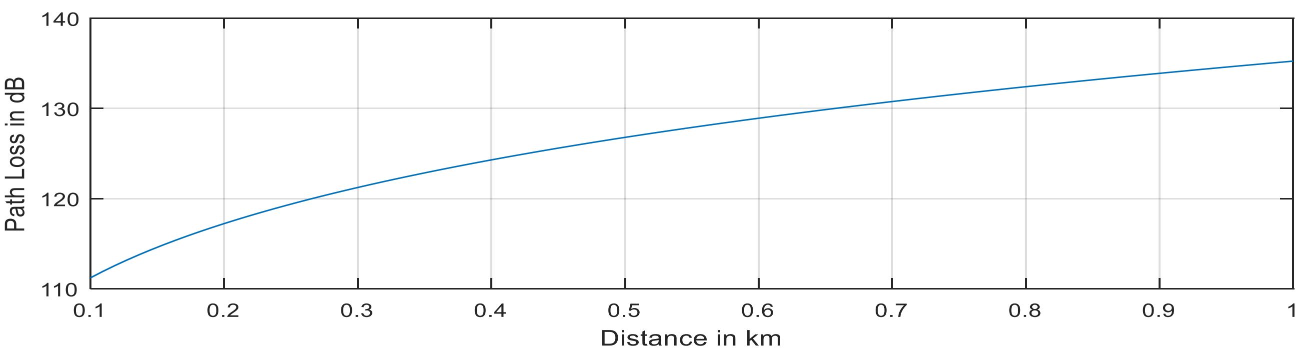
$$G_r = \left[42.57 + 13.7\log_{10} f\right]\left[\log_{10} h_r - 0.585\right] \quad (14)$$

and for large city environments,

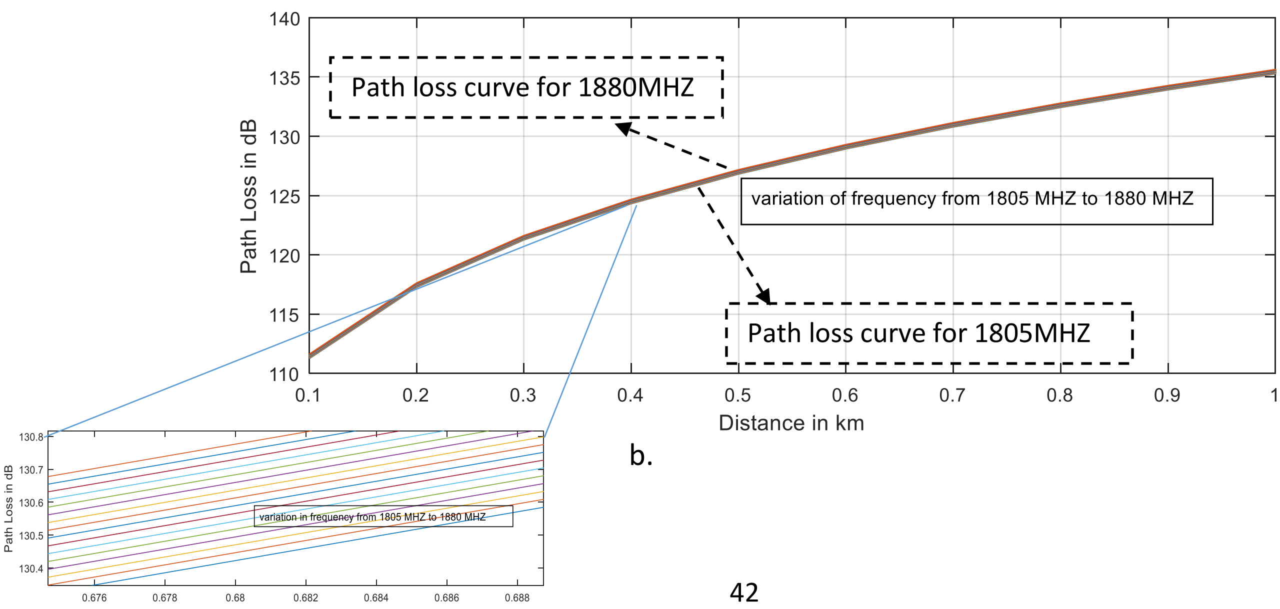
$$G_r = 0.759h_r - 1.862 \quad (15)$$

where, f is the frequency in GHz, d is the distance between base station and mobile station in km, h_b is the BS antenna height in metres and h_r is the MS antenna height in metres.

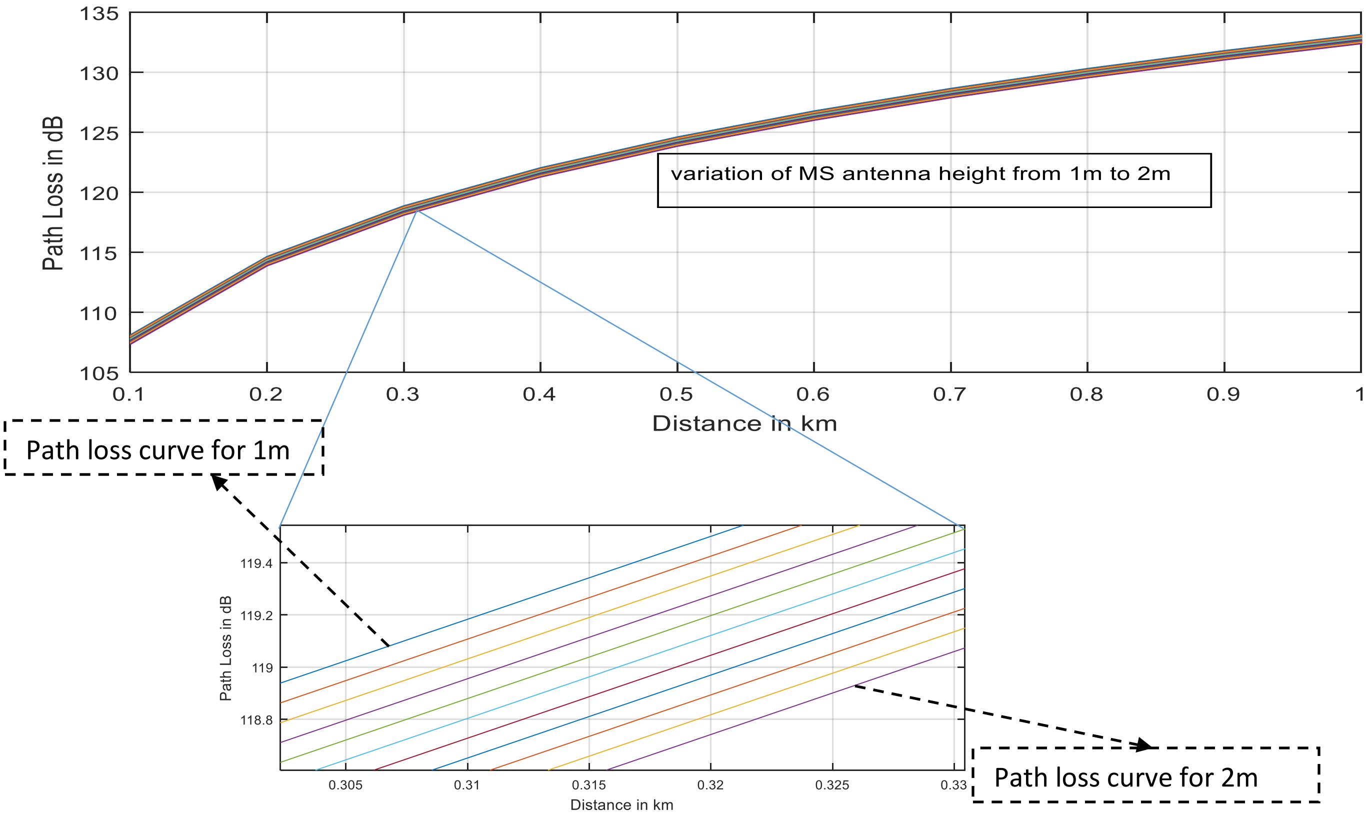
From the path loss equation of ECC-33, we can see that the path loss depends on distance between BS and MS, frequency of operation, MS antenna height and BS antenna height. It is important to see how the path loss is affected with the variation of each parameter. The graphs below shows the path loss at varying values of parameters. Urban model is used for the analysis.



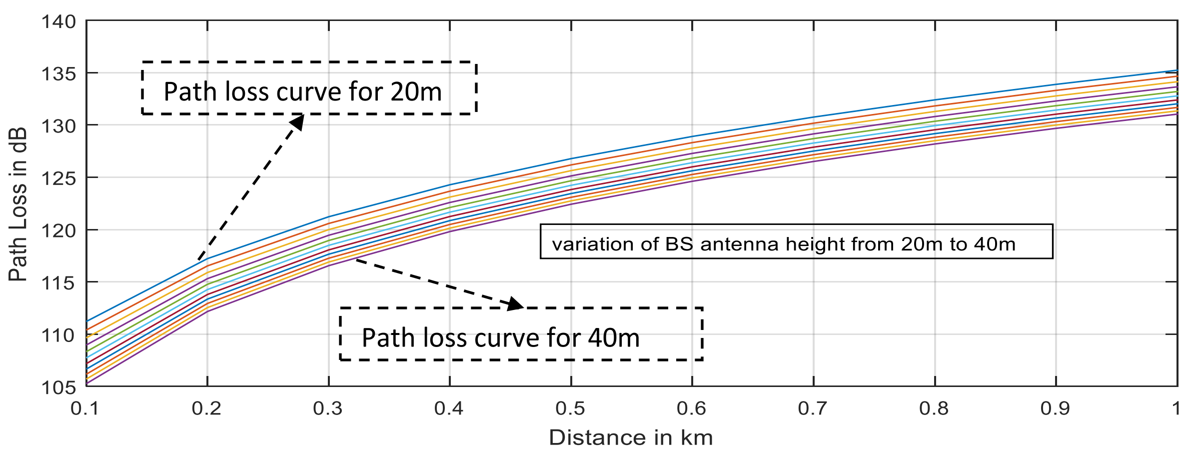
a.



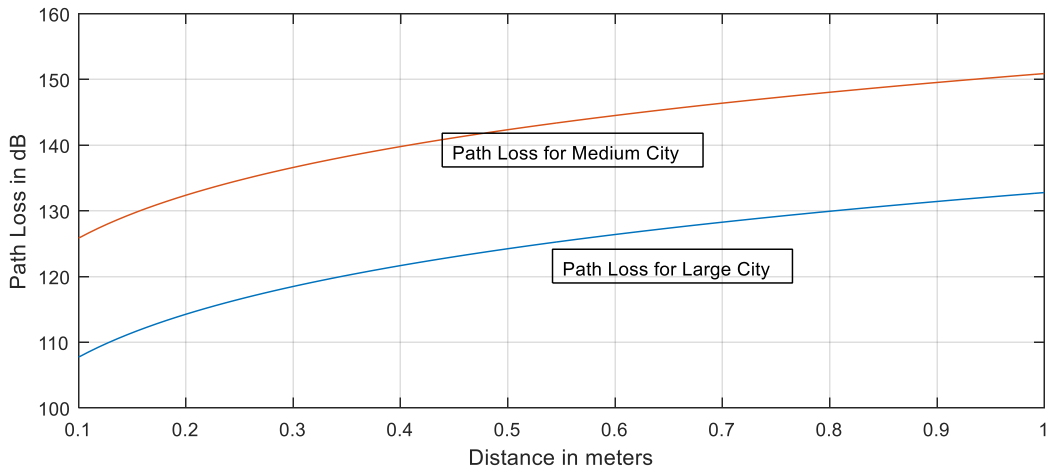
b.


135
130
125
120
115
110
105
Path Loss in dB
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Distance in km
variation of MS antenna height from 1m to 2m
Path loss curve for 1m
119.4
119.2
119
118.8
Path Loss in dB
0.305
0.31
0.315
0.32
0.325
0.33
Distance in km
Path loss curve for 2m

c.


140
135
130
125
120
115
110
105
Path Loss in dB
Path loss curve for 20m
variation of BS antenna height from 20m to 40m
Path loss curve for 40m
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Distance in km

d.



e.

Figure 8 Path loss with ECC-33 model in a. Variation of distance b. Variation of frequency c. Variation of transmitting antenna heights and d. Variation of receiving antenna heights e. Medium and Large City Path Loss

The path loss in ECC-33 increases as the separation between the BS and MS increases as shown in Fig. 13 a. The rate of increase of the path loss is higher in smaller distances. As expected, path loss always increases with distance. When frequency increases from 1805 MHZ to 1880 MHZ, path loss increases by 0.58dB. So the lowest curve in Fig. 13b is the one whose frequency is 1805 MHZ. Still similar to SUI model, the path loss in ECC-33 also changes insignificantly due to variation of frequency. The path loss in ECC-33 model decreases as the MS antenna height increases. For example, an increase in the MS antenna height causes the path loss in Fig.13c to decrease by 0.76dB regardless of distance. Similarly, an increase of BS antenna height from 20m to 40m will cause a variation in the path loss (a decrease as height increases) from 5.95dB to 4.21dB as the distance increases from 0m to 1200m. Expressed in easy way, path loss in ECC-33 decrease on average by 4.57dB when BS increases from 20m to 40m.

2.4.3. COST231

COST 231 is the most widely used path loss model for mobile wireless system[3]. Like ECC-33, It was also developed as an extension of Hata-Okumura model to support a frequency band from 500MHZ to 2000MHZ, BS antenna height from 30m to 200m and MS antenna height from 1m to 10m [18]. For higher frequencies correction factors are presented [10]. The model can be used to estimate path loss for Urban, Suburban and Rural areas.

The basic equation for path loss in dB is ,

$$PL = 46.3 + 33.9log_{10}{}^{f} - 13.82log_{10}{}^{h_b} - a_{hm} + \left(44.9 - 6.55log_{10}{}^{h_b}\right)log_{10}{}^{d} + c_m \text{ ------------(16)}$$

where, f is the frequency in MHz, d is the distance between BS and MS antennas in km, and h_b is the BS antenna height above ground level in metres. The parameter c_m is defined as 0 dB for suburban or open environments and 3 dB for urban environments.

The parameter a_{hm} is defined for urban environments as

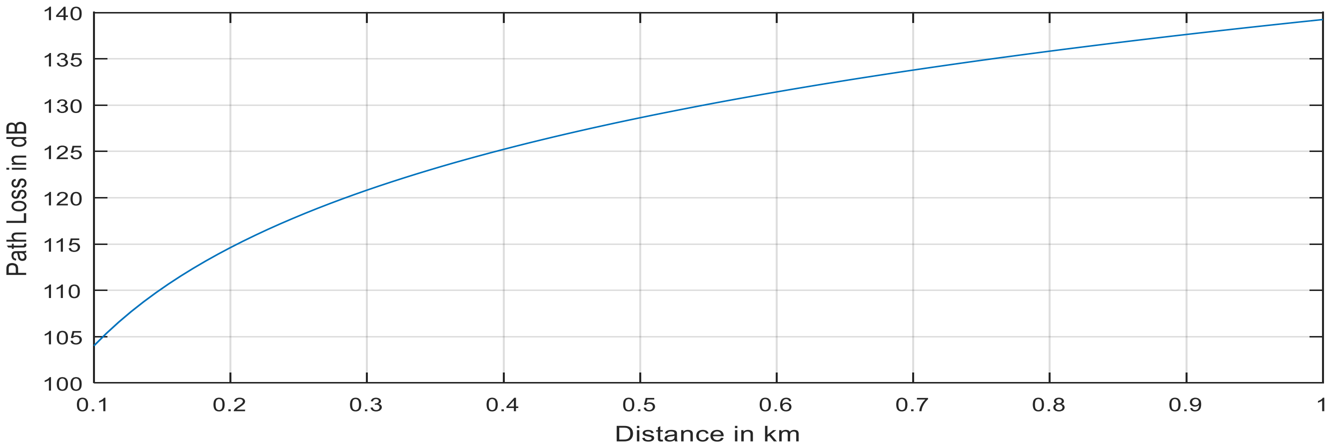
$$a_{hm} = 3.20\left(log_{10}{}^{11.75h_r}\right)^2 - 4.97, \; for\ f > 400\ MHz \text{ ---(17)}$$

and for suburban or rural (flat) environments,

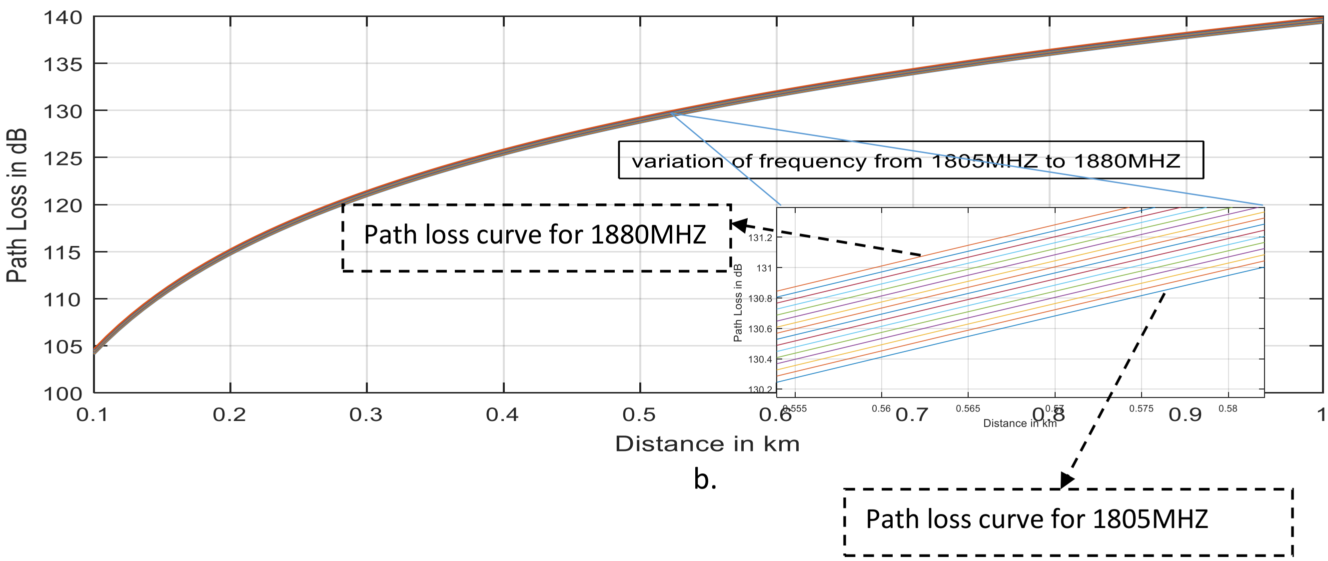
$$a_{hm} = \left(1.1log_{10}{}^{f} - 0.7\right)h_r - \left(1.56log_{10}{}^{f} - 0.8\right) \text{ --(18)}$$

where, h_r is the MS antenna height above ground level [3][4][5].

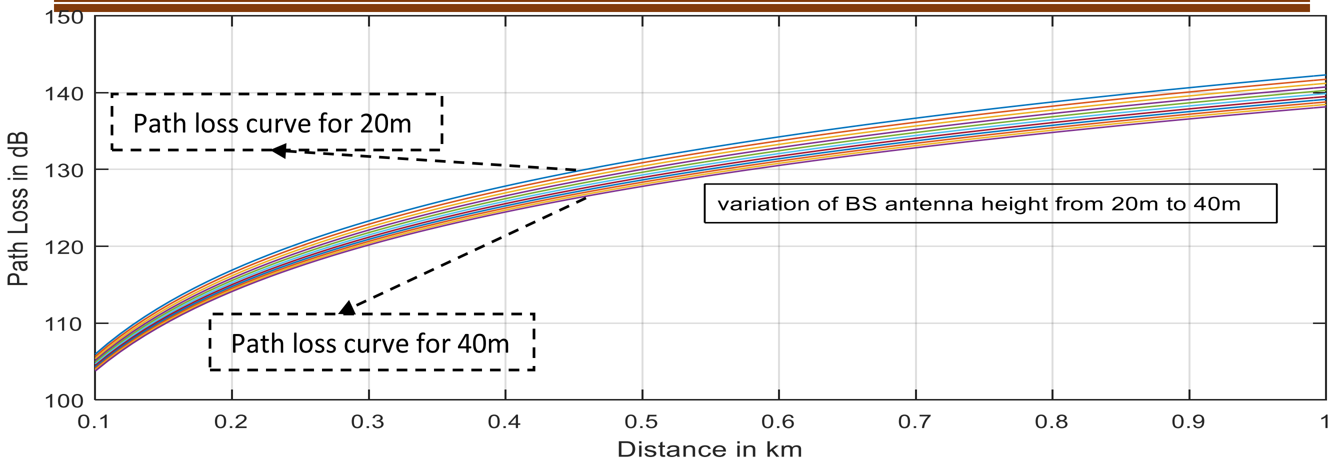
It is easy to observe that the path loss in COST 231 depends different factors as distance, frequency, MS antenna height and BS antenna height. It is necessary to study how the path loss responds to the different variation of the parameters. Urban model is used to show. The graph below depicts the variations.


Path Loss in dB
Distance in km
140
135
130
125
120
115
110
105
100
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

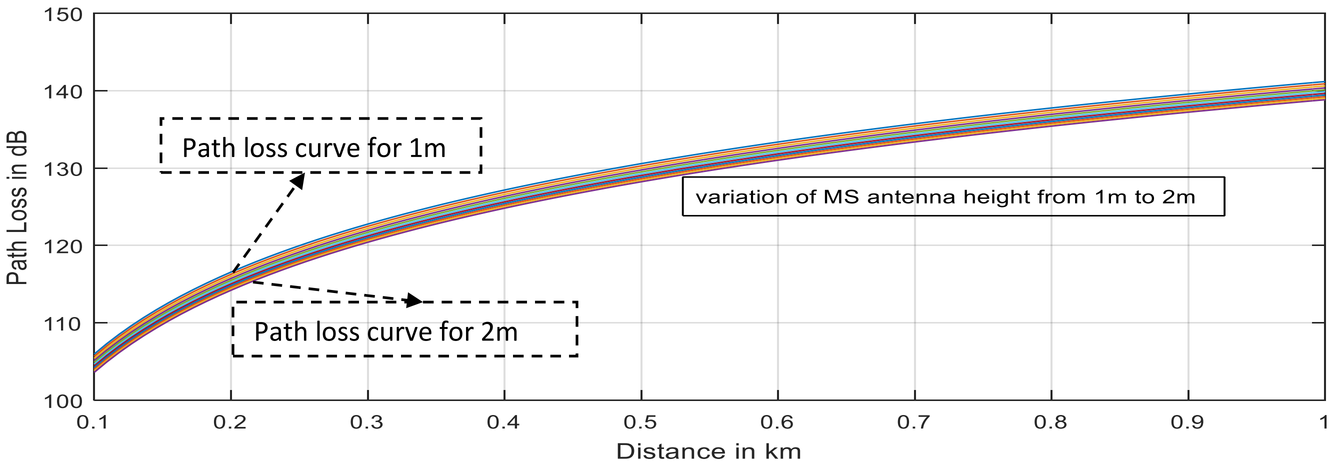
a.


Path Loss in dB
Distance in km
variation of frequency from 1805MHZ to 1880MHZ
Path loss curve for 1880MHZ
Path loss curve for 1805MHZ
140
135
130
125
120
115
110
105
100
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

b.



c.



d.

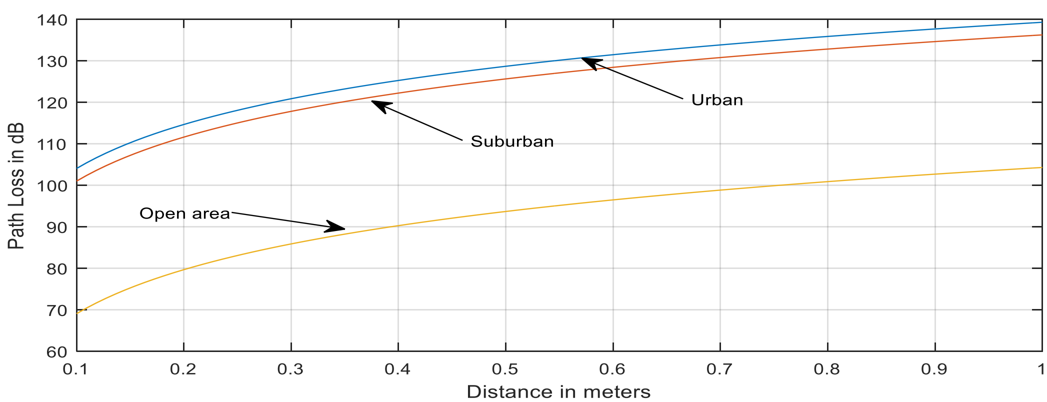


Figure 9 Path loss with COST231 model in a. Variation of distance b. Variation of frequency c. Variation of transmitting antenna heights and d. Variation of receiving antenna heights e. Urban, Suburban and Open

The path loss in COST231 is increasing with distance similar to ECC-33 and SUI path loss models do. The increment is faster for lower values of distance (fig. 14a). It is a global fact that path loss increases with distance. It is again expected that path loss increases with frequency if all other parameters are kept the same. Fig.14b also proves this fact. The lowest graph is a path loss for 1805 MHZ whereas the highest one is for 1880 MHZ. There is a decrease in the variation of path loss from 13dB to 8.4dB with an increase of BS antenna height from 20m to 40m with distance increase from 0m to 1200m (fig.14c). The lowest graph being the one with the BS antenna height is 40m and the highest is for 20m BS antenna height. Unlike the variation in BS antenna height, MS antenna variation is not dependent on distance. Ofcourse path loss decreases with increase of MS antenna height. 2.35dB variation in path loss is observed with an increase of MS antenna height from 1m to 2m.

Path loss model	**Distance from 0 to 1200m**	**Frequency from 1805MHZ to 1880MHZ**	**BS antenna height from 20m to 40m, distance from 100 to 1200m**	**MS antenna height from 1m to 2m**
SUI	PL increases from 121dB to 184dB	PL increases by 0.46dB	PL decreases and variation increases from 0 to 5.02dB	PL decreases by 3.25dB
ECC-33	PL increases from 107dB to 135dB	PL increases by 0.58dB	PL decreases and variation decreases from 5.95dB to 4.21dB	PL decreases by 0.76dB
COST231	PL increases from 104dB to 142dB	PL increases by 0.6dB	PL decreases and variation increases from 2.19dB to 4.32dB	PL decreases by 2.35dB

Table 3 SUI, ECC-33 and COST231 path loss models and their responses to changes in parameters

From the three path loss models, we can learn that each model responds differently to changes of their parameters. All the three are similar in that they have common parameters. The table below shows path losses and their parameters.

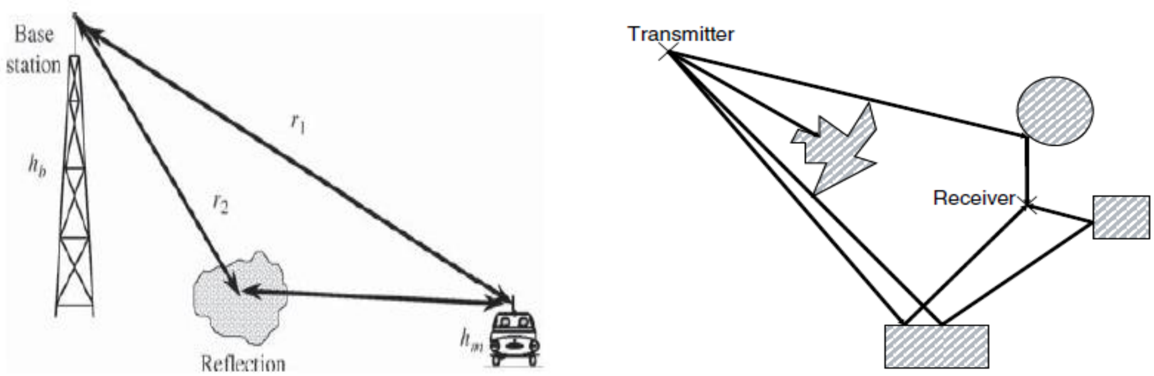
Note: that all the manipulations done here in this table and in the above three models are with the following values of parameters. Distance is from 0 to 1200m, frequency = 1800MHZ, hb = 30m and hr = 1.5m.

As can be seen from the table above, the path loss estimated by SUI is higher than ECC-33 and COST231 in the range from 0m to 1200m. All the three models seem to respond negligible to changes in the carrier frequencies whereas they have significant path loss difference for the change of BS antenna heights. The rate at which the path loss decreases with increase of BS antenna height is increasing in the case of SUI and COST231 and decreasing for ECC-33. An increase of MS antenna height keeps the path loss decreasing in all the three models but the magnitude can be ignored in the case of ECC-33 but not in the other two.

3. Radio Wave Propagation

Wireless communication uses air/space as a medium to transfer information from transmitter to receiver. Variations in the amplitude, phase and frequency of the radio waves (i.e. known as modulation) is used to carry the information. There are a lot of barriers the radio waves has to pass to reach to the transmitter. The barriers could be air, buildings, cars, forests, water bodies, mountains, etc. Depending on the type of transmission, the radio wave may face one or more of the barriers stated above. The easiest way of transmission is a line of sight (LOS) in which there is only air between the transmitter and the receiver. Remote controllers, Microwave transmissions, communications between mobile terminals etc require LOS. But this will not happen in many wireless communications as the information sender and information receiver are at far distances. Cellular communications, Satellite communications, Broadcast communications, HF/VHF/UHF communications, etc are among the wireless communications that will have barriers other than air between transmitter and receiver, none line of sight (NLOS) [17]. The signal in the NLOS transmission will exhibit Reflections, Diffractions and Scattering [18]. This is known as propagation path loss. This propagation loss should be calculated to determine the coverage boundaries of the wireless communications.

Cellular communications also use radio waves and hence the path loss should be determined to decide the coverage boundaries of the base stations. The magnitude of the losses depend on many factors such as frequency, morphology type, base station and mobile station antenna heights etc. Large scale and small scale (fading) propagation models needs to be carefully studied to get a complete picture of the channel in a particular environment.



(a) (b)

Figure 10 A figure showing (a) Line of Sight (LOS) and (b) Non Line of Sight (NLOS) connectivity of radio waves [20]

3.1. Basics of Propagation

To understand the basics of propagation and hence the propagation models, we should first understand about the three basic propagation mechanisms: Reflections, Diffractions and Scattering. Reflection is the bouncing off of a radio wave from an object of a size much larger than the wave length of the radio wave. The reflection could occur as the radio wave propagates from the base station and hits the earth, buildings, cars, people, forest, waterbodies etc. Cellular communication takes advantages of this reflection to give coverage on spots where the base station maynot directly access. The direction and amount of reflection depends on the material type, material geometry, angle of incidence, polarization and frequency of the wave. Diffraction is a phenomenon that occurs when the radio wave hits objects which have sharp edges. The radio wave after diffracting throght the obstacle will happen to change its direction of travel. This will make wireless communications possible even when there is no line of sight between the transmitter and receiver. As an example, a transmitter in one side of a mountain can communicate with a receiver in the other side of the mountain with no need of installing retransmitter in the tip of the mountain. Refraction also depends on the geometry of the objects, amplitude and phase of the wave, and polarization of the incident wave at the point of diffraction. Scattering happens when the radio wave pass through a medium in which it contains numerous objects per unit volume with size less than the wavelength [19].

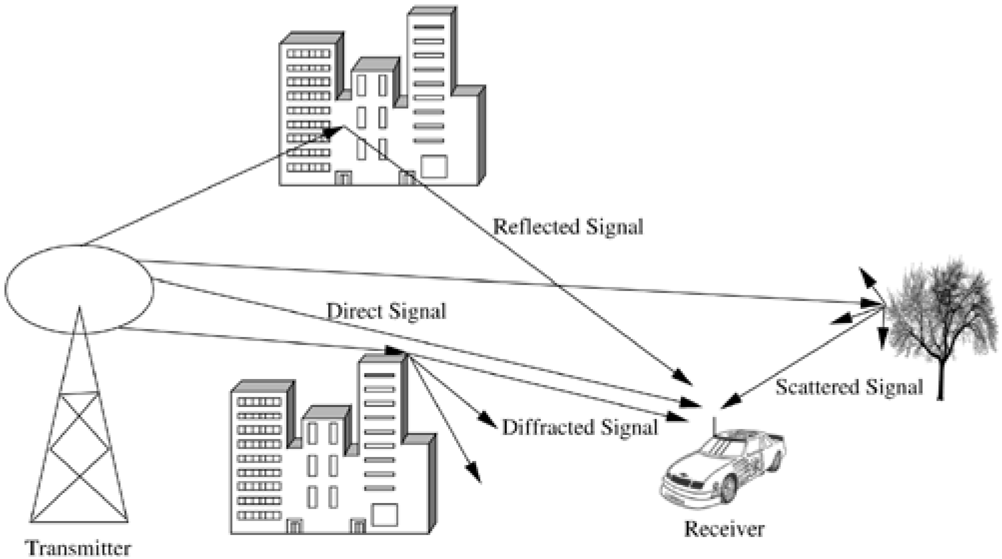


Figure 11 Propagation Mechanisms [31]

3.2. Small Scale Effects and Large Scale Effects

A mobile terminal receives a signal from the base station from different paths. We can categorize the way the signal reaches the terminal into three. Some signals can reach directly. Some of them will reach after hitting obstacles such as folds, buildings, structures whose sizes are larger than the wave length of the signal. Still the remaining will arrive after hitting small objects (smaller than the wave length of the signal) with sharp edges. So whatever may be the way the signal can reach the receiver, it will suffer the following attenuations: Propagation loss, Large Scale Fading, Small Scale Fading [20][21]. The signals which reach the receiver directly (passing only through air or without being hit by any obstacles) will have a propagation path loss due to the air through which the signal passes. Propagation loss (also known as Transmission loss) is caused due to the distance the signal travels. The amount of path loss is dependent mainly on distance (the length the signal travels). It is also dependent on frequency, antenna gains and other losses such as antenna loss, transmission line attenuation, etc. such a propagation loss is most often expressed by the Friis Free Space Propagation Model. It is a linear loss in the logarithmic scale.

$$P_r(d) = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2 L} \quad \text{---} (1)$$

Where $P_r(d)$ is the received signal power in watts as a function of distance between transmitter and receiver , P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength and L is other losses that is not associated with propagation loss.

But in reality, the signals are reaching the receiver in different pathways. One, as stated above, is by hitting obstacles such as folds, buildings, structures whose sizes are larger than the wave length of the signal. This will cause slow variations of the signal over the distance between the transmitter and receiver. This variation of the signal is called large scale fading, also known as slow fading, shadow fading and long term fading. Experiments prove that log-normal distribution obeys the large scale fading.

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma x} e^{-(\ln(x)-\mu)^2/2\sigma^2} \quad \text{---} (2)$$

Figure 3 below show a typical measured data and a log-normal distribution curve.

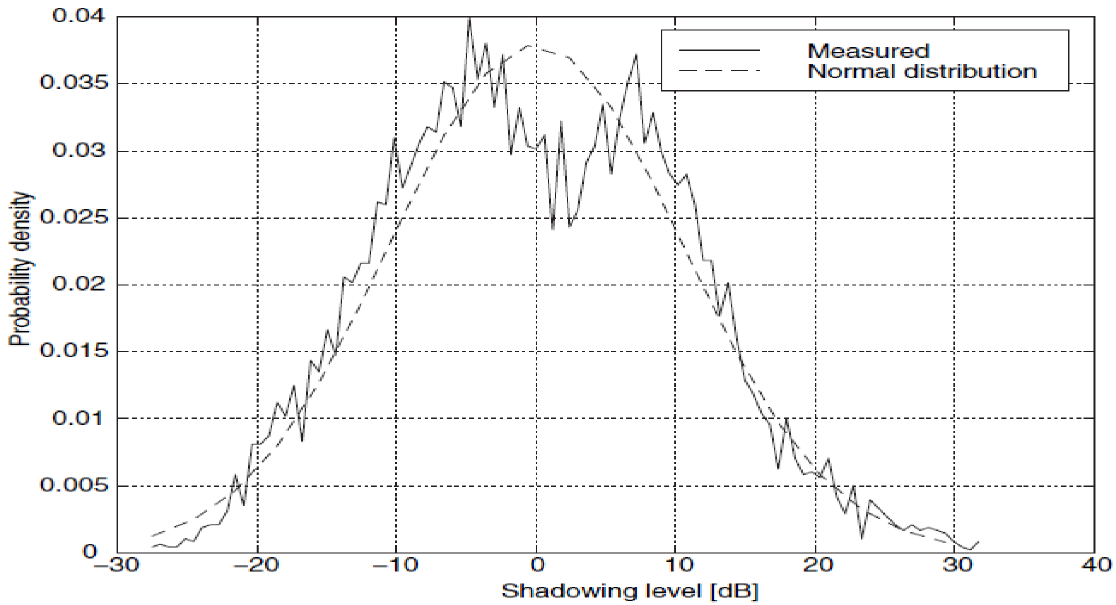


Figure 12 Probability density function of shadowing [21]

Still the third way the signal reaches the receiver is stated as one that will arrive after hitting small objects (smaller than the wave length of the signal) with sharp edges. The sharp edges will make the signals scattered, reflected and absorbed. Part of them will miss the receiver and the other parts will be received. Losses due to this are termed small scale fading, also known as multi-path fading, fast fading, short term fading. Small scale fading is a rapid change in signal strength within short distance and time [19][21]. It follows a Rayleigh distribution. Factors influencing small scale fading are multipath propagation (Reflection objects), speed of the mobile (Doppler shifts), speed of surrounding objects and transmission bandwidth of the signal. The different types of small scale fading are flat fading, frequency selective fading, fast fading and slow fading [21]. Flat fading results when the bandwidth of the signal is less than band width of the channel and delay spread is less than the symbol period whereas the reverse effect will result in frequency selective fading. Fast fading occurs due to high Doppler spread, coherence time less than symbol period and channel variations faster than base band signal variations. The figure below shows the path loss, large scale fading and small scale fading.

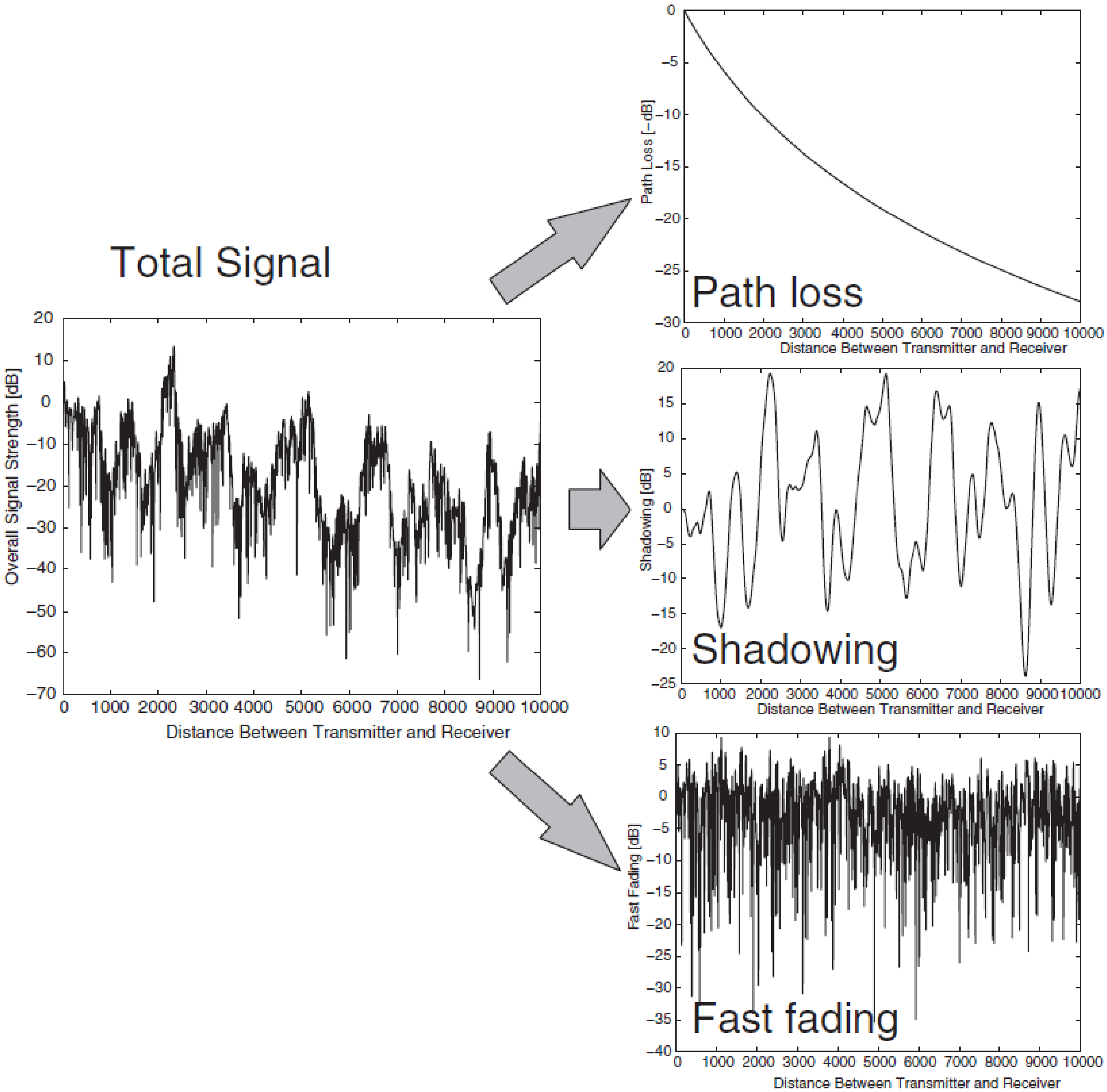


Figure 13 Path loss, Shadowing (large scale fading) and Fast fading (small scale fading) [20]

3.3. Fading Channels

The figure below shows details of the fading channels.

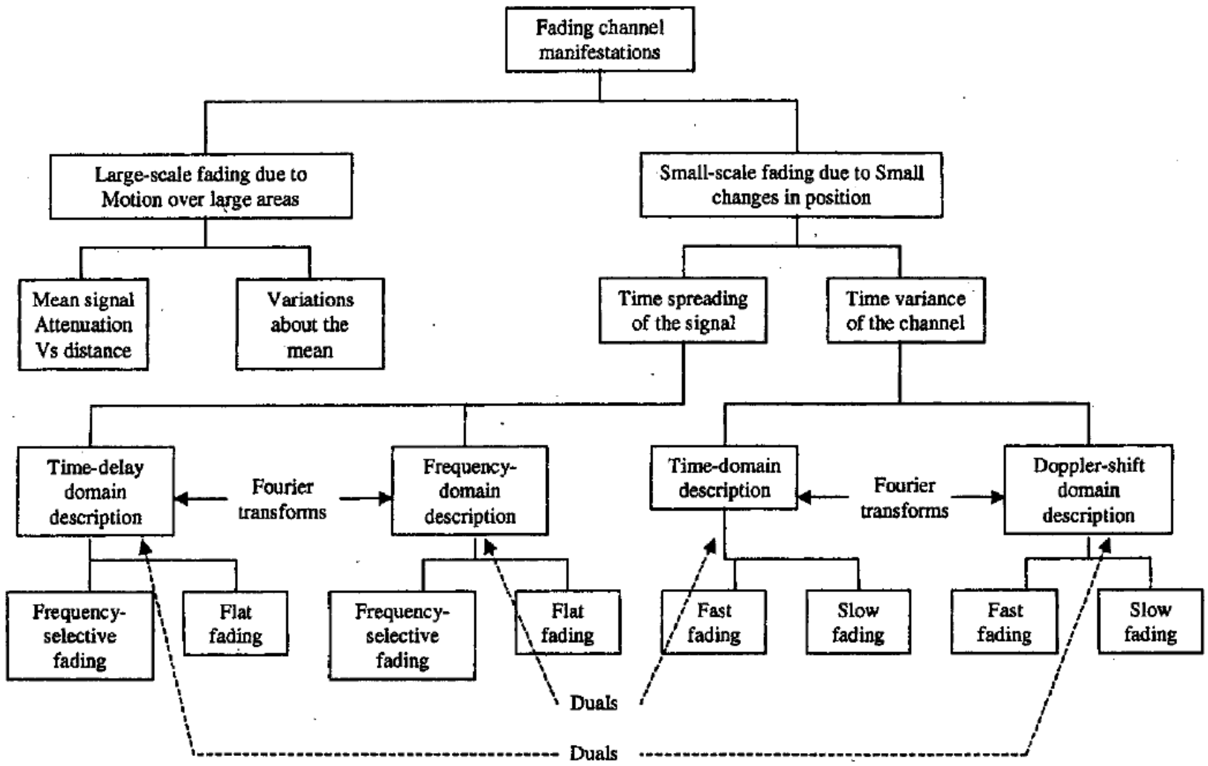


Figure 14 Fading Channels [28].

4. Measurement Procedures

In a path loss model tuning, field data measurement is a very critical process. The result is fully dependent on these data. A wrong field data measurement may result in a wrongly tuned path loss model. Wrong data measurement may happen due to various reasons. Selection of proper site is one of the ways that can contribute to the right field data measurement. The other factor is choice of the right tools. Field data measurement tools use different hardware and software tools and these tools should be selected and calibrated (configured) properly to get the right data measurement that can reflect the effect of the area in focus. If base station antennas are used for measurement, the coverage area of the sector should first be determined before taking the measurement. Measurements can also be biased by the speed of the drive when the measurement was taken. Consistency of using the same measurement tools, weather condition, traffic movement, etc are also factor that can contribute to the correct field data measurement.

4.1. Selection of Sites for Measurement

Addis Ababa city has different area types. Some areas have high density of buildings, more traffic, etc. Other areas have some buildings, some traffic flow and living houses. There are also areas having open spaces and only some living houses. This tells us that AA has urban, suburban and open area morphologies. This means that we cannot consider the whole of AA as a single morphology type. Before taking measurements, planning was done to decide where the measurements should be taken. A google earth assisted and physical observation planning was done and 28 sites were selected to represent the open areas, suburban areas and urban areas of AA. For the sake of this work, a sector is considered as a site. In that case, a base station having three sites may be considered as three sites. Since one sector is facing to one side of the area and the other one to the other side, the measurement actually represents two different areas. Base stations of 2G and 3G technologies (GSM and UMTS) were used for measurement.

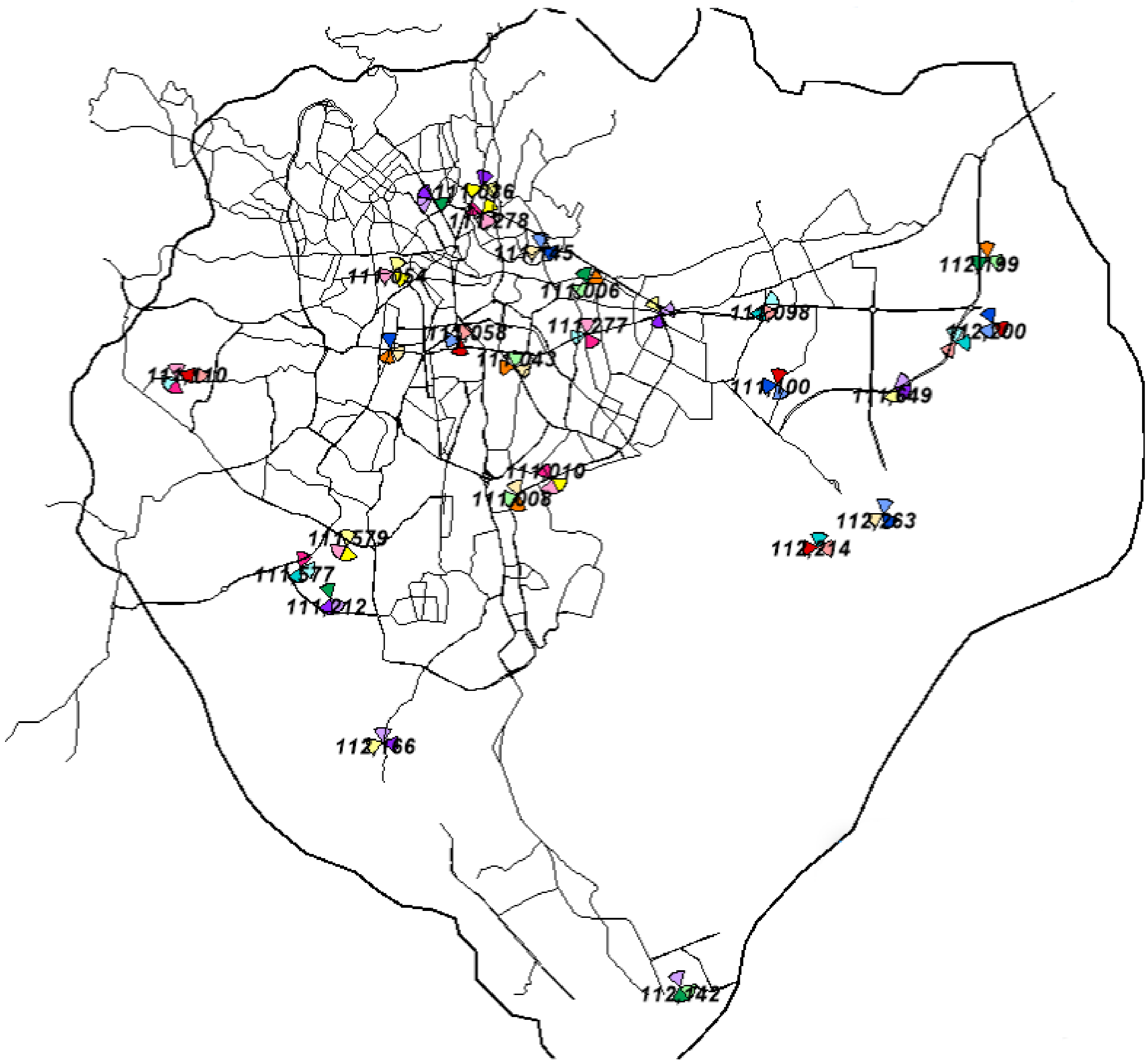


Figure 15 Selected sites in AA city map

4.2. Measurement Tools

Tools are critical for the Drive Test (DT) data collection methods. In the data collection, I have used all tools from ethio telecom. The tools (hardware tools and software tools) used are the ones used for their day to day DT operation. They are all quality tools with their commercial licenses. The data was also taken by the experts from engineering department in ethio telecom.

At the start of the DT measurement, data has been collected for a site (Lideta site with ID 111645) two times to check for the consistency of the measurement. The Root Mean Square Error (RMSE) of the two data is calculated to be 8.47dB which is an acceptable value. The difference can also be accounted for the difference in the traffic situation, weather situation [30] and other environmental situations when measurements have been taken. There are two options to use for the DT software, Nemo outdoor and Nemo handy. I have tried to use both but the measurement made by the Nemo handy is generally lower (signal levels are lower) than that of the Nemo outdoor. The RMSE value between the two measurements is also higher than 10dB. This difference was also observed by experts of ethio telecom. To avoid inconsistency of the measurement, I have left data collection using the Nemo Handy.

Distances from the BTS	Average signal level (+/-5m) from first measurement	Average signal level (+-5m) for second measurement
100	-68.8	-58.78
150	-64	-60
200	-69.17	-81.83
250	-67	-64.44
300	-66.14	-63.43
350	-68.17	-66.86
400	-72.6	-67.8
450	-75.8	-68.2
500	-76	-70.86
550	-77.4	-70.13
600	-79	-72.83
650	-78.75	-72.25
700	-83.71	-72.61
750	-81.5	-76.67
800	-75.75	-69.36
850	-71.13	-63.2
900	-64.23	-61.14
950	-63.86	-57.91
1000	-69	-53.18
1050	-65.64	-60
1100	-93.5	-71.89
1150	-86	-87

Table 4 Sample path loss measured values

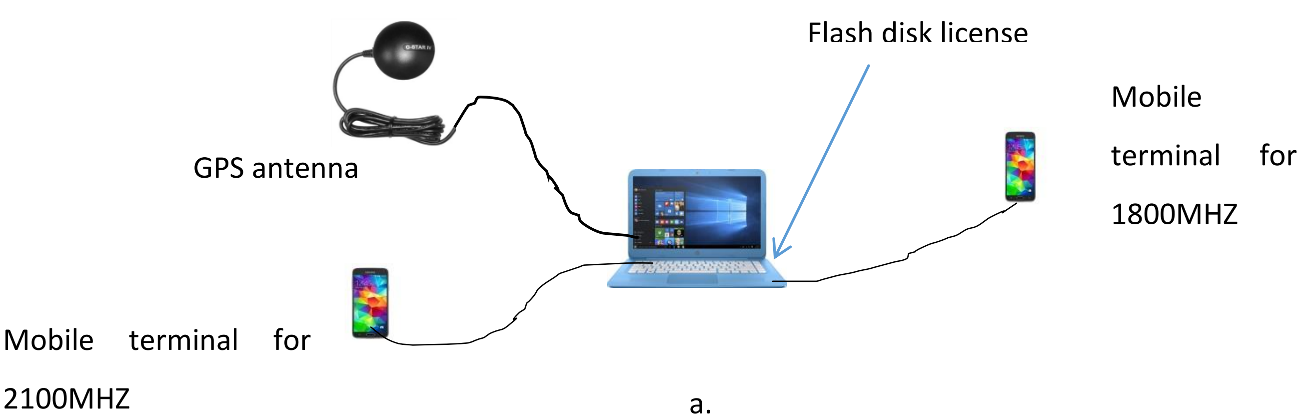
The following tools have been used to do the drive test data collection.

No	Name	Version	License required(YES/NO)
1	Nemo Outdoor	7.8.0.8	YES
2	Nemo router installed SAMSUNG Mobile phone	SAMSUNG Galaxy S5	YES(Online activated license)
3	GPS	Garmin 18	No
4	Frequency Scanner with GPS	Nemo	YES
5	Laptop	Lenovo Core i7	
6	Car charger for Laptop & Frequency Scanner	NA	NA
7	Actix Analyzer	5.1	No License

Table 5 Measurement Tools

4.3. Measurement Procedures

The field data collection is carried out by setting the tools in a car and driving along the coverage area of the sector. The tools shown in the above table are connected to each other in fig 16.



a.

b.

Figure 16 Measurement setup a. Schematic diagram b. real drive test setup

Here are the procedures when measurement is taken:

1.Devices are first interconnected. The two Samsung S5 mobiles (one for 1800MHZ and the other for 2100MHZ) are connected to the laptop. Similarly the GPS antenna and the flash stick (License) are also connected to the computer.

2.Laptop and mobile terminals are powered up and Nemo outdoor in the laptop & Nemo router in the mobile terminals are started.

3. Nemo outdoor is set to idle mode, i.e. a mode that enables to measure a signal strength of Broadcasting Control Channel (BCCH) in GSM for 1800MHZ and Pilot Scrambling Code (PSC) in UMTS for 2100MHZ with no traffic (a mode used to test coverage of a sector). A mode that enables to measure signal strength traffic channel (TCH) by making traffic is called dedicated mode. This mode is not used here as it measures only quality (i.e. signal to interference ratio).

4.The Nemo outdoor is set to system locking. One terminal is locked to GSM and the other to UMTS. Then carrier lock is configured. GSM is locked to 1800MHZ and UMTS is locked to 2100MHZ. Finally channel locking is configured. GSM is locked to BCCH channel and UMTS is locked to PSC channel.

5. Measurement can now be started by clicking run button. We can measure distance from the BS while driving and see the signal strength at each point.

Note that the system takes measurement in each second. The distance the measurement is taken depends on speed of drive. A drive speed of 30km\h will cover 8.33m in one second. So the drive speed is limited to as low as possible (a maximum of 30km\h) to avoid data missing at required spots (i.e. a factor of 50m).

4.4. Measurement Challenges

Although data collection is a major part of the model tuning process, it cannot be done easily and with very high accuracy. A lot of challenges are there that may distort the accuracy of the measurement. The amount of biasness the challenges have may differ from one to the other. One of the challenges is that a drive test route follows roads and these roads will take us out of the coverage of the sector. This will cause a measurement to be taken at a point where the sector is not supposed to cover. It will show mostly either no signal or a very bad signal. This problem is almost unavoidable since there is no way I can know whether I am in the coverage area of the sector or not. The figure below illustrates this case. The one shown with arrow lines is the coverage area of the sector for a site ID 111579 but the road will force us to go the way shown in the bold line.

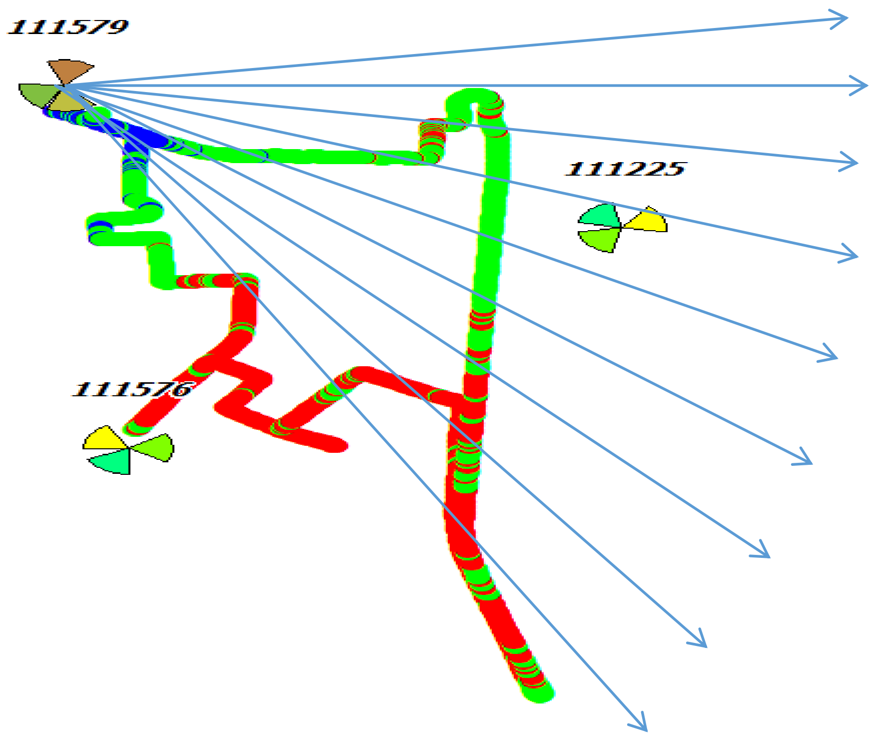


Figure 17 DT route during data collection for site ID 111579

The second challenge is that it is impossible to make data collection in all the required points of the sector's coverage. As clearly known, an antenna will radiate its signal in its main and side lobes. So measurements have to be taken in representative points of these lobes coverage but due to unavailability of road only measurements at some points are taken. Weaker signal strengths are measured if side lobes are accessed whereas strong signal are measured if the main lobe is accessed. Both ways will cause measurement biasness.

The third challenge is that antennas are down tilted (both mechanical and electrical tilting) in a way they can cover only the required areas, mostly not more than 700m for the case of AA. But measurements are taken for distances until 1200m from the base station as large scale path loss models require [20] and are the case in most literatures reviewed [3] [10][11]. This may lead to the same problem stated in the second challenge.

The fourth challenge is that measurements have been taken during the rainy season (from 7/7/2018 to 8/28/2018). A paper in [30] concludes that atmospheric changes have effects on measured signal strength, i.e. signal strengths measured at the same point but in different seasons (atmospheric effect) will result in different values. Hence, data measurements have to be taken in all the seasons to avoid biasness of the result.

The fifth challenge is that the transmission power of one BS is different from the other. Path loss is highly dependent on the transmission power as stated in equation 3. But for the sake of simplifying the calculation, the most common transmission power level is taken as a representative value for all the BSs considered.

Other challenges have also encountered during measurements. In some scenarios, a co-channel might have been involved in the measurement. A temporary object in an area may also bias the measurement. BS and MS Antenna heights are also different in different measurement points but an average antenna height is taken to simply calculations. Effect of antenna height is seen in the previous chapter.

4.5. Error Measurements and Model Tuning

4.5.1. Error Measurements

Four types of error measurement techniques are used in this thesis to measure the errors between the estimated data by the path loss models and measured values. The four techniques are Root Mean Squared Error (RMSE), Mean Error (ME), Standard Deviation (SD) and Mean Absolute Percentage Error (MAPE).

RMSE is the most used technique almost in all the literatures[1][2][3][5]. It is also mainly used in this thesis to measure errors and make comparison among path loss models. RMSE aggregates errors at various times into a single measure.

It is calculated by the following formula.

$$RMSE = \sqrt{\frac{1}{n}(\sum_{1}^{n} PL_m - PL_p)^2} \quad \text{-----(19)}$$

Where n – is the number of measured data

PL_m – is the measured data

PL_p – is the predicted data

The second error measurement technique is the Mean Error (ME). It measures the mean (center) of the errors between the predicted and measured values. Its formula is

$$ME = \frac{1}{n}\sum_{1}^{n}(PL_m - PL_p) \quad \text{---} (20)$$

The standard deviation (SD) measures the magnitude of variation of the errors (between predicted values and measured values) from the Mean Error(ME). It is expressed as

$$SD = \sqrt{\sum_{1}^{n}((PL_m - PL_p) - ME)^2} \quad \text{---}(21)$$

Mean Absolute Percentage Error (MAPE) is one of the measures of prediction accuracy. It has the following formula.

$$MAPE = \frac{1}{n}\sum_{1}^{n}| PL_m - PL_p | / PL_m \quad \text{---}(22)$$

We use this measure as a second option because it has some drawbacks like it doesn't allow zero value of measured data and biased on the value of the predicted data (when it is either too low or too high).

4.5.2. Model Tuning

Path loss models may not fit to the environment in focus as they are in their original form. They must be tuned towards the measured data. Linear Least Square Method (LLSM) is used to tune the models. LLSM is a simple method, easy to implement, suitable to optimize environmental factors and the most used method of tuning. It is required to change the empirical models in linear equation form to use this model. The equation below shows the linear least square method (LLSM).

$$e(a,b)=\sum_{i=1}^{n}(y_i-P(a,b))^2 \quad \text{-----(23)}$$

Where e(a,b) is error function, y_i is the measured path loss values and P(a,b) is the equation of the empirical path loss model.

Path loss model is said to be tuned at values of a and b when the equation (23) is driven for minium value of e(a,b). The minimum value of e is obtained by setting the first derivative of the equation is equal to zero. Two linear equation with variables of a and b can be obtained. Solving the equations simultaneously results in the solutions for a and b interms of the measured values and known values from the empirical model equations. The detail tuning equations are shown in appendix A, appendix B and appendix C.

5. Analysis and Discussion of Results for 1800MHZ and 2100MHZ

The list below shows the site list for which measurements have been done with their design parameters. For 1800MHZ, measurement up to a distance of 1200m was taken whereas for 2100MHZ, measurement up to 700m was taken. Since the BS for UMTS was designed to cover only small coverage areas, taking measurement beyond this distance will give only a no signal. Moreover, higher frequencies will not travel much compared to lower frequencies. Not on all points the signal strength was captured, there are missing points. These points are assumed to be no coverage points. For the sake of analysis, -108dB is replaced in these vacant spaces assuming the terminals sensitivity is -107dB. The other thing to consider is to determine the representative values of signal strength at the required points. One option is to take the value measured at the required spot and the other option is to take the average value within some distance range or time range. Measurement of signal strength at a point in time range was not made and hence not taken as an option here. Moreover, taking the measurement on the spot was not considered due to:

1. Since I have only 23 points (every 50m beginning from 100m to 1200m) to consider for analysis, taking the value on the spot will have big biasing effect on the result. The value on the spot could be no coverage but may have good value of signal strength within some centimeters range. Large scale path loss models consider only the over trend at larger distances as indicated in Section 2.2 of Chapter 2.
2. Measurement is taken with a drive test. Depending on the speed, the distance gap between the measurements will vary. There is a high chance that the measurement is missed at the required spot. Analysis for this is given in Section 4.2 of Chapter 4.

The remaining option is to take the average value. But the question here is what distance range should be taken to average. An intuitive is considered and signal strengths within +/-5m from the required spot are averaged and taken as representative points for the required spot.

5.1. Site Specific Data Analysis for Urban, Suburban and Open Areas Propagation Models

During selection of the sites, I have tried to proportionate the number of sites from the three area types urban, suburban and open areas. The verdict is made by looking at the areas from google earth and physical observation. The actual classification should be based on the path loss exhibited in the particular area. That is how path loss models classify the area type as urban, suburban and open (rural). As detailed in section 2.4 of chapter 2, SUI, ECC-33 and COST 231 have variants based on area types. Let me now classify the selected sites based on closeness of the signal strength to the different variants of the path loss models. RMSE is used as a measure of closeness.

Path loss calculations are required to see the general pathloss trend of a site or see the path loss trend in the selected points. Path loss calculations are made based on equation (4) shown in Chapter two. The equation is stated as, $PL = P_{tx} - P_{rx}$. P_{rx} is the received power and it is obtained by measurement and P_{tx} is the transmitted power. The transmitted power is obtained from the configuration of each site. Each site in 1800MHZ (GSM) is configured with 43dBm as a default power. There are some situation where the default power maynot be the actual power allocated for the site. Otherwise most sites are operating with this power. Moreover the sites are set to power level 0, meaning that the TRX uses all the power allocated. Hence 43dBm is used for the calculation of path loss and anywhere required for 1800MHZ (GSM).

Below is the screen shot of some sites as a sample from the network management system (NMS). As we can see from the screen shot, the power level configured is 0 (third column) and the transmit power ranges from 400dBm to 430dBm (column 4) but the majority of the power configuration is 430dBm as can be observed from the NMS.

List Device Attributes of TRX

TRX ID	TRX Name	Power Level	GBTS Power Type(w	eGBTS Power Type(0.1dBm)	TRX Priority
2148	111231_Kolfe Police Training Center_G2-35	0	<NULL>	417	Level0
2149	111417_Wereha Yekatit School_G2-2	0	<NULL>	430	Level0
2150	111168_Kirkos Tele_D2-2	0	<NULL>	408	Level0
2151	111178_Gafa Kedanemihret_G10	0	<NULL>	430	Level0
2152	111870_G1-4	0	<NULL>	430	Level0
2153	111178_Gafa Kedanemihret_G12	0	<NULL>	430	Level0
2154	111870_G1-5	0	<NULL>	430	Level0
2155	111870_G2-6	0	<NULL>	400	Level0
2156	111870_G2-7	0	<NULL>	400	Level0
2157	111212_Lebu_G10	0	<NULL>	408	Level0
2158	111212_Lebu_G11	0	<NULL>	408	Level0
2159	111212_Lebu_G20	0	<NULL>	400	Level0
2160	111168_Kirkos Tele_D3-3	0	<NULL>	408	Level0
2161	111212_Lebu_G30	0	<NULL>	408	Level0
2162	111172_Areke Fabrica_D1-37	0	<NULL>	408	Level0
2163	111120_Lafto Tele_G10	0	<NULL>	408	Level0

Figure 18 Screen shot of TRX attributes for 1800MHZ (GSM) from NMS

Regarding 2100MHZ (UMTS), the same transmit power (43dBm) is used as GSM. Here also there are also sites whose power is configured to be different from 43dBm but the majority of the sites are operating at 43dBm. PCPICH is configured to take 10% out of the total transmission power allocated for the BS (43dBm). Note that 43dBm is equivalent to 20watt and 10% of 20watt is 2watt and this is equivalent to 33dBm. So for calculation of path loss for 2100MHZ here and anywhere in this thesis is taken to be 33dBm.

Below is shown the power configuration of PCPICH and Total transmission power taken from the NMS. As shown in the figure, 33dBm is configured for PCPICH and 43dBm is configured for total transmission power. Note that the power values shown from the NMS screen should be multiplied by 0.1dBm to change to dBm both for 1800MHZ (Figure 18) and 2100MHZ (Figure 19 and 20)

List PCPICH

Logical RNC ID	Cell ID	Cell Name	PCPICH ID	PCPICH Transmit Power	Max Transmit Power of PCPICH	Min Transmit Power of PCPICH
101	31048	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U32	2	330	346	313
101	31047	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U31	2	330	346	313
101	31046	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U23	2	330	346	313
101	31045	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U22	2	330	346	313
101	31044	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U21	2	330	346	313
101	31043	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U13	2	330	346	313
101	31042	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U12	2	330	346	313
101	31041	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U11	2	330	346	313
101	55703	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U43	2	330	346	313
101	55702	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U42	2	330	346	313
101	55701	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U41	2	330	346	313
101	55553	112094_DG_WL_GUL_BSCRNC1.HW.ABNFEDPOLBLD.WAAZ.AA_U43	2	330	346	313
101	55552	112094_DG_WL_GUL_BSCRNC1.HW.ABNFEDPOLBLD.WAAZ.AA_U42	2	330	346	313
101	55551	112094_DG_WL_GUL_BSCRNC1.HW.ABNFEDPOLBLD.WAAZ.AA_U41	2	340	346	313
101	35709	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U33	2	330	346	313
101	35708	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U32	2	330	346	313
101	35707	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U31	2	330	346	313
101	35706	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U23	2	330	346	313
101	35705	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U22	2	330	346	313

Figure 19 Screen shot of PCPICH for 2100MHZ (UMTS) from NMS

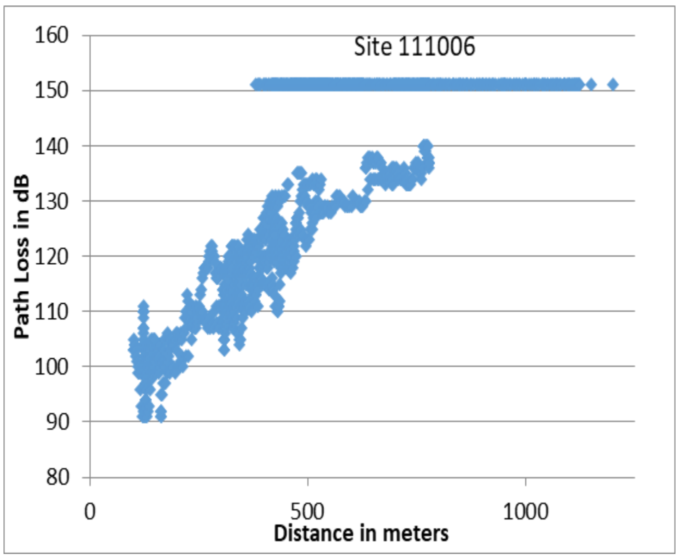
List Cell Basic Information

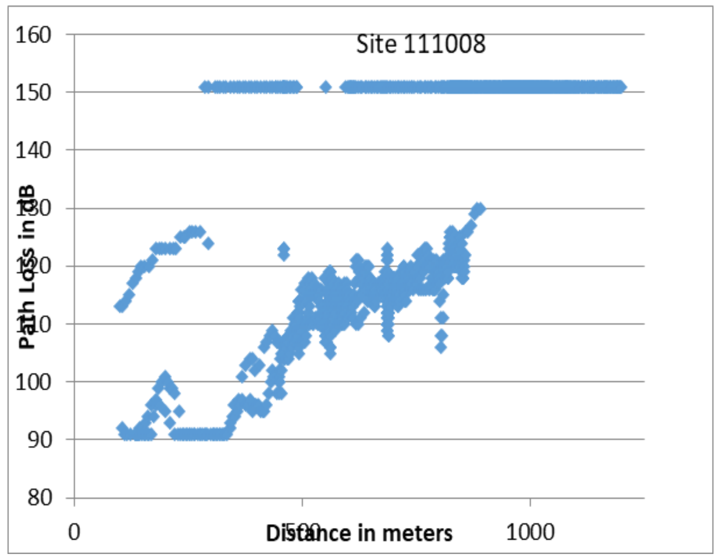
Logical RNC ID	Cell ID	Cell Name	Max Transmit Power of Cell	Band Indicator	Cn Operator Group Index	UL Frequency Ind	Up
101	31048	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U32	430	Band1	0	TRUE	96
101	31047	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U31	430	Band1	0	TRUE	96
101	31046	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U23	430	Band1	0	TRUE	97
101	31045	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U22	430	Band1	0	TRUE	97
101	31044	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U21	430	Band1	0	TRUE	97
101	31043	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U13	430	Band1	0	TRUE	97
101	31042	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U12	430	Band1	0	TRUE	97
101	31041	111104_H4_DG_WL_GUL_BSCRNC1.HW.GOLAMICHLCHU.NAAZ.AA_U11	430	Band1	0	TRUE	97
101	55703	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U43	430	Band1	0	TRUE	96
101	55702	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U42	430	Band1	0	TRUE	96
101	55701	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U41	430	Band1	0	TRUE	96
101	55553	112094_DG_WL_GUL_BSCRNC1.HW.ABNFEDPOLBLD.WAAZ.AA_U43	430	Band1	0	TRUE	96
101	55552	112094_DG_WL_GUL_BSCRNC1.HW.ABNFEDPOLBLD.WAAZ.AA_U42	430	Band1	0	TRUE	96
101	55551	112094_DG_WL_GUL_BSCRNC1.HW.ABNFEDPOLBLD.WAAZ.AA_U41	430	Band1	0	TRUE	96
101	35709	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U33	430	Band1	0	TRUE	96
101	35708	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U32	430	Band1	0	TRUE	96
101	35707	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U31	430	Band1	0	TRUE	96
101	35706	112110_DG_WL_GUL_BSCRNC1.HW.YKNGATKOKSCH.CAAZ.AA_U23	430	Band1	0	TRUE	97

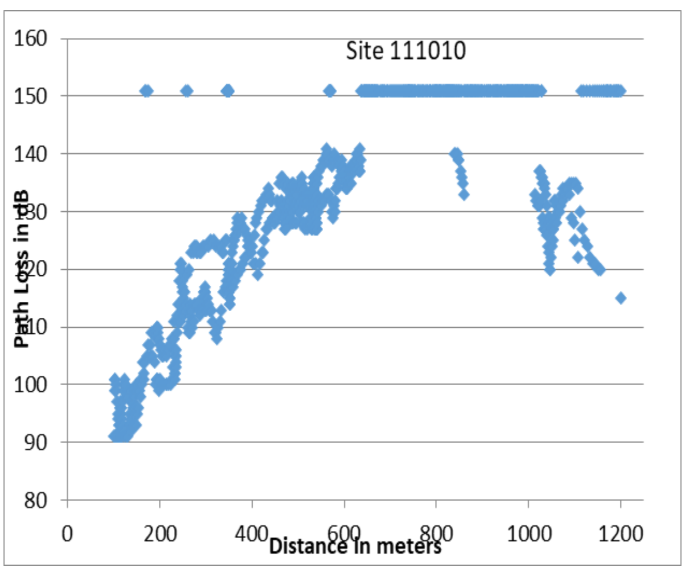
Figure 20 Screen shot of total transmission power for 2100MHZ (UMTS) from NMS

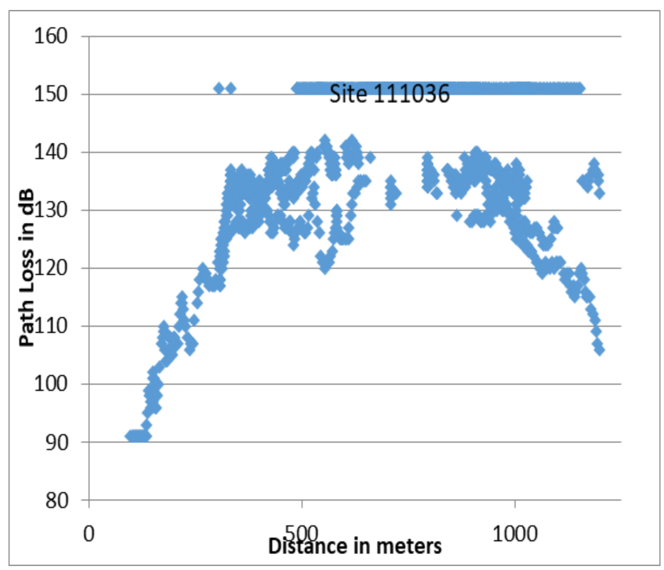
5.1.1. General Data Trend

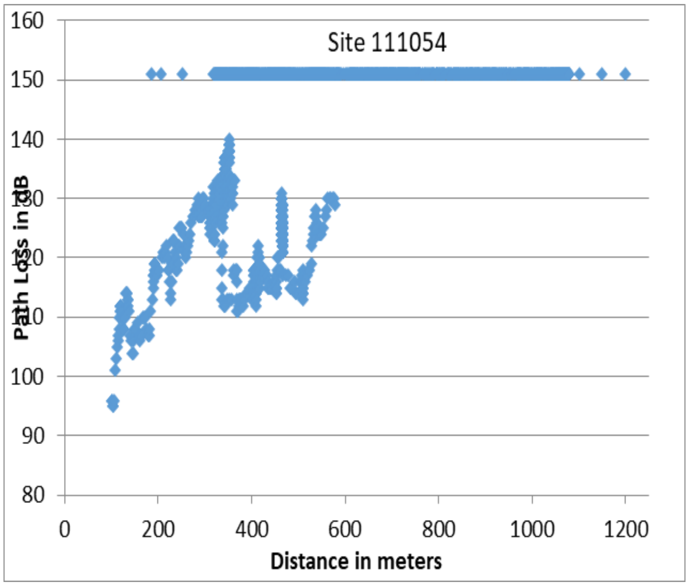
Among the 28 sites surveyed, 23 were fit enough to be analyzed. Depending on the speed of drive a different number of data were gathered for each site from which an average value was calculated for further analysis. Let us now see the general trend of the signal strength with distance. Below are shown the trend of the measured data.

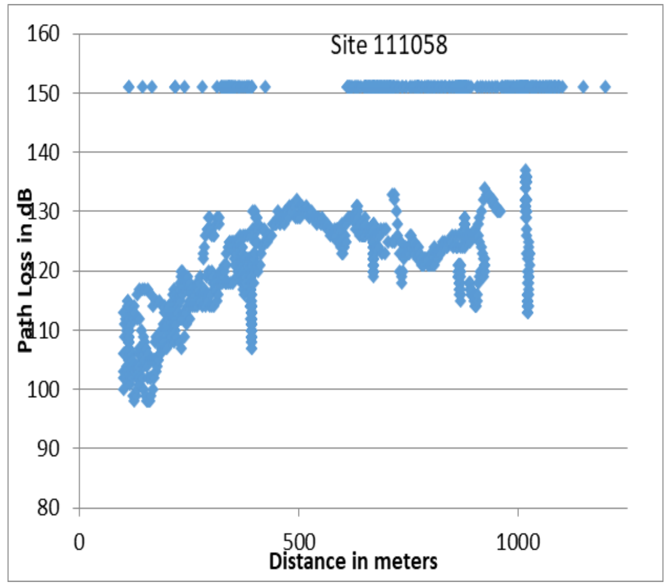


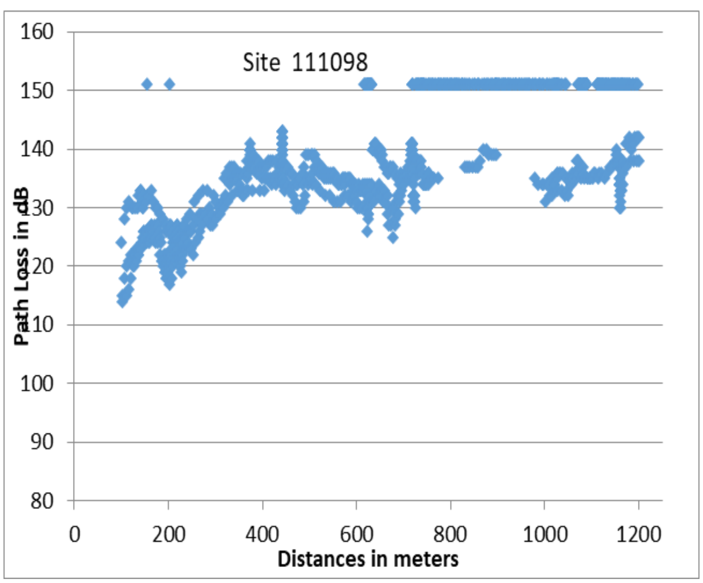


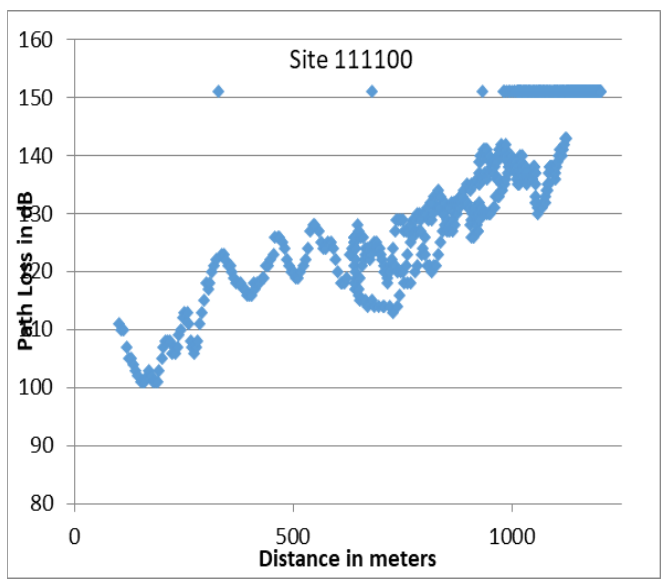


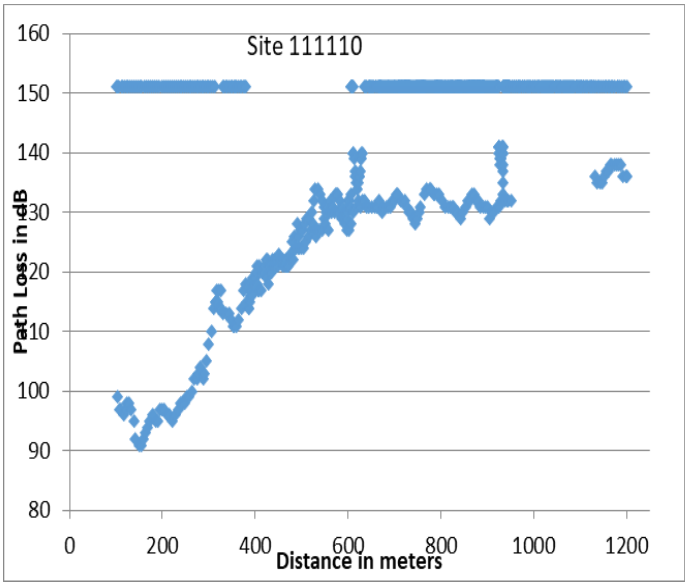


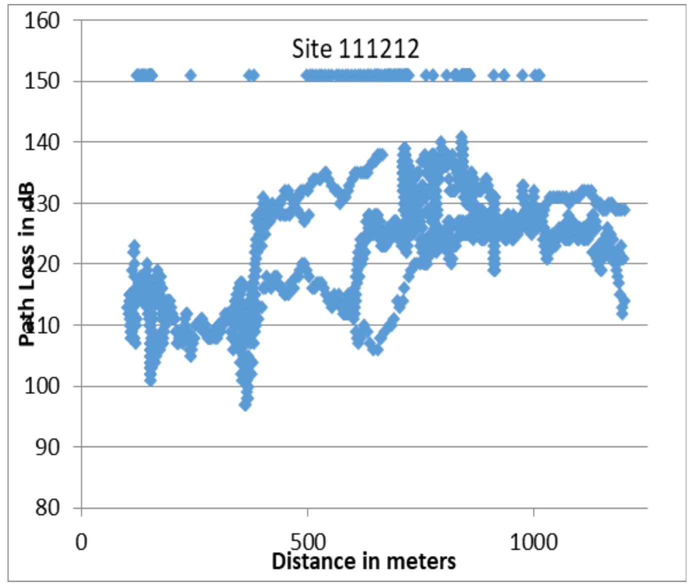

Site 111054
Path Loss in dB
Distance in meters

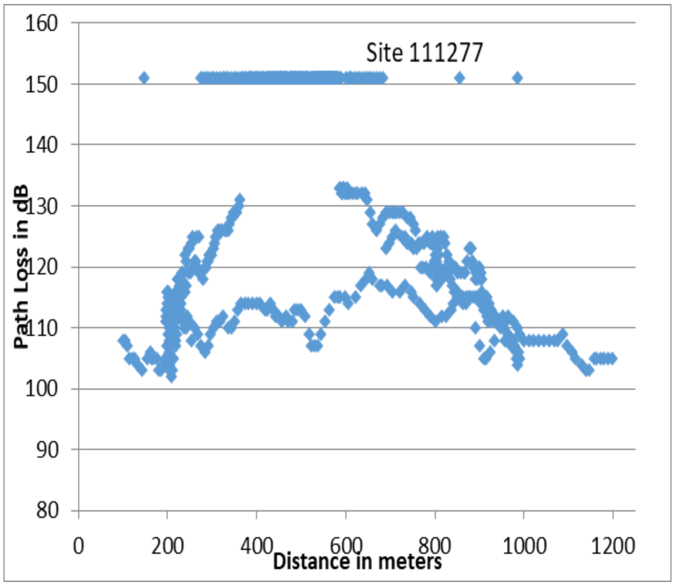

Site 111058
Path Loss in dB
Distance in meters

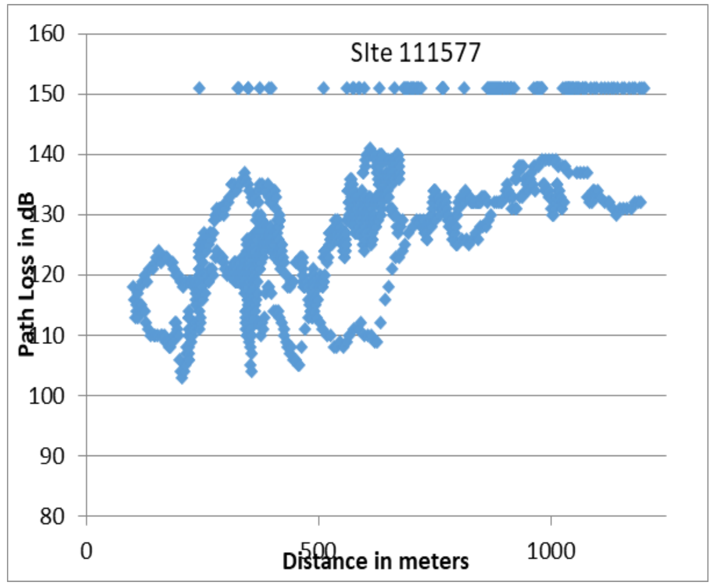

Site 111098
Path Loss in dB
Distances in meters

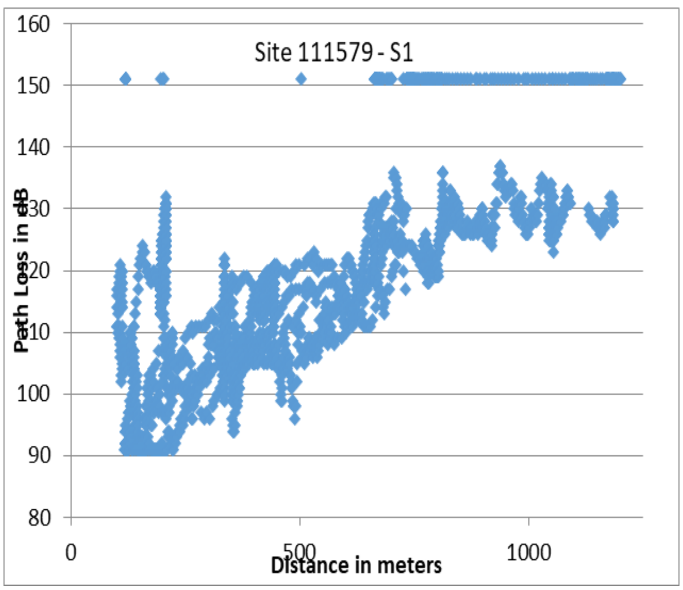

Site 111100
Path Loss in dB
Distance in meters

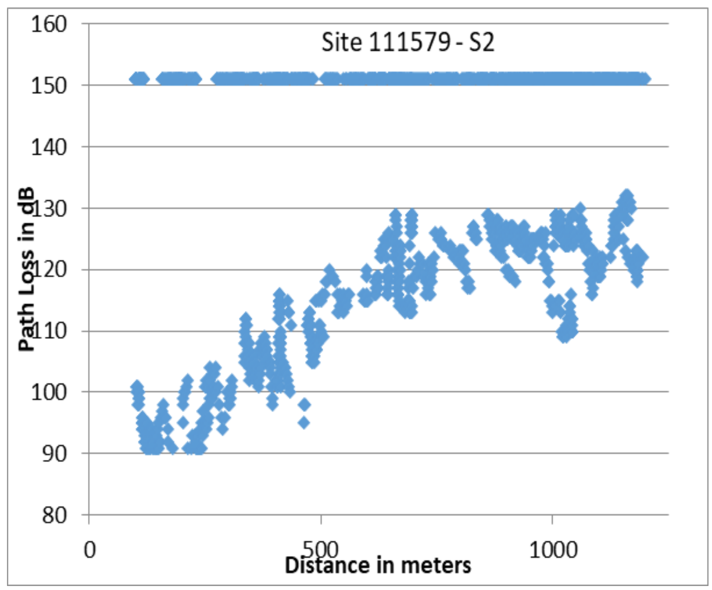

Site 111110
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200

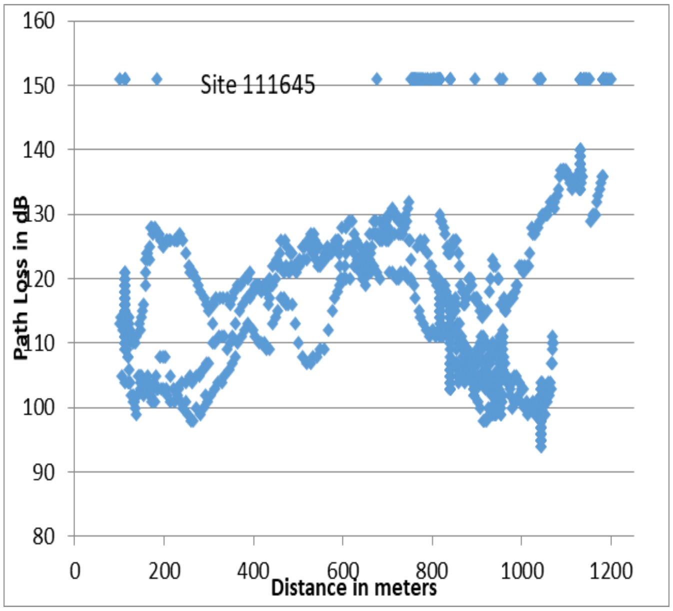

Site 111212
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
500
1000

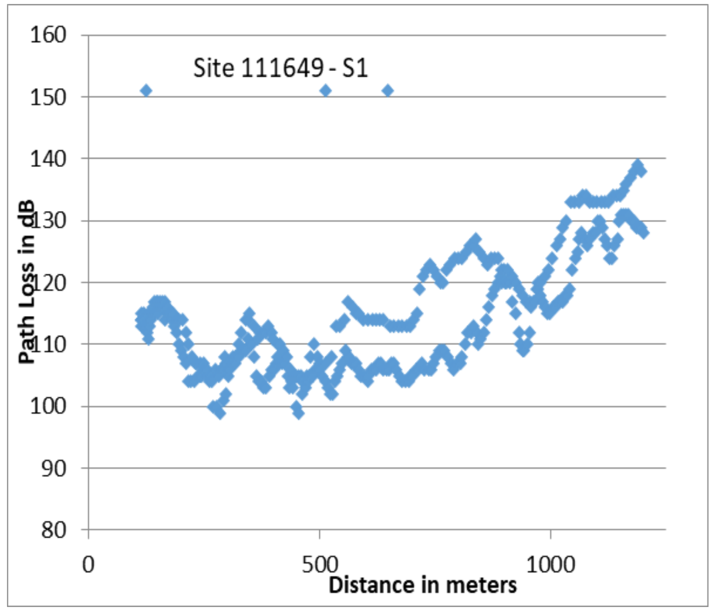

Site 111277
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200

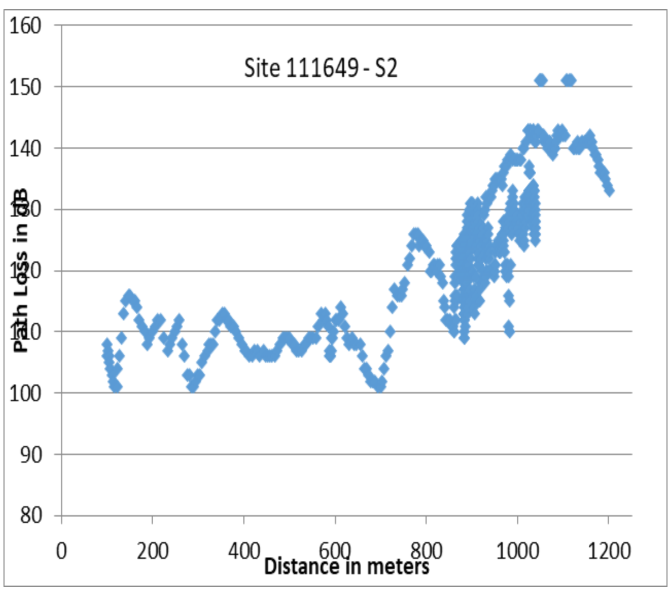

SIte 111577
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
500
1000

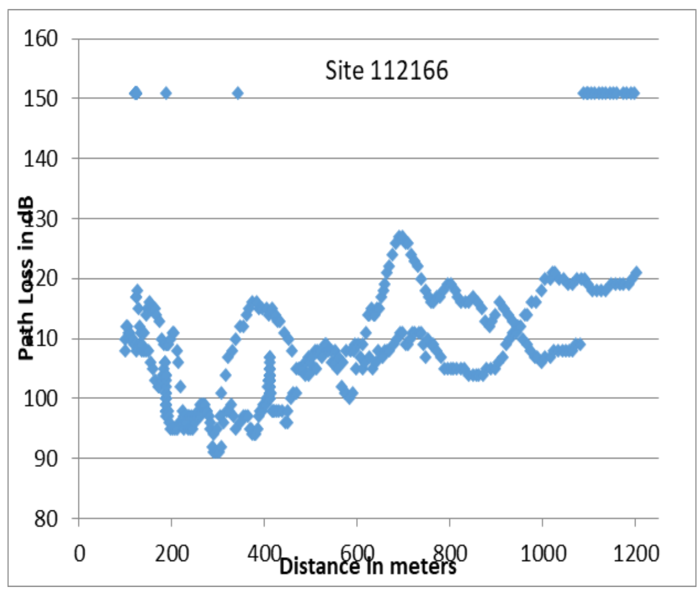

Site 111579 - S1
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
500
1000

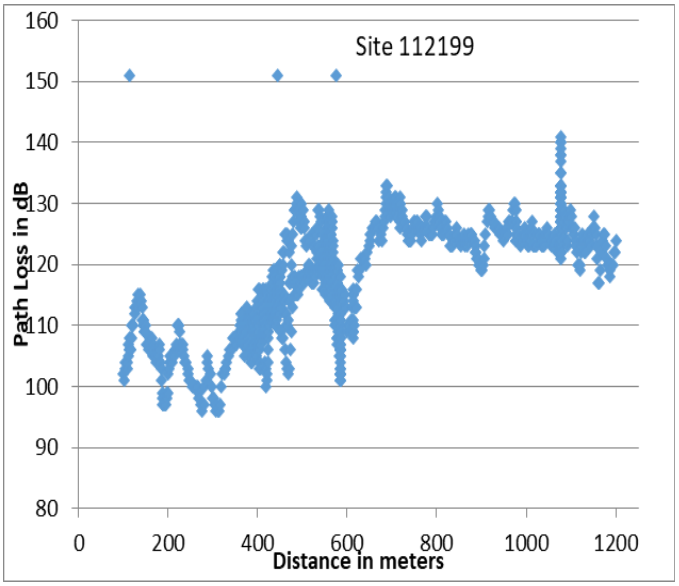

Site 111579 - S2
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
500
1000

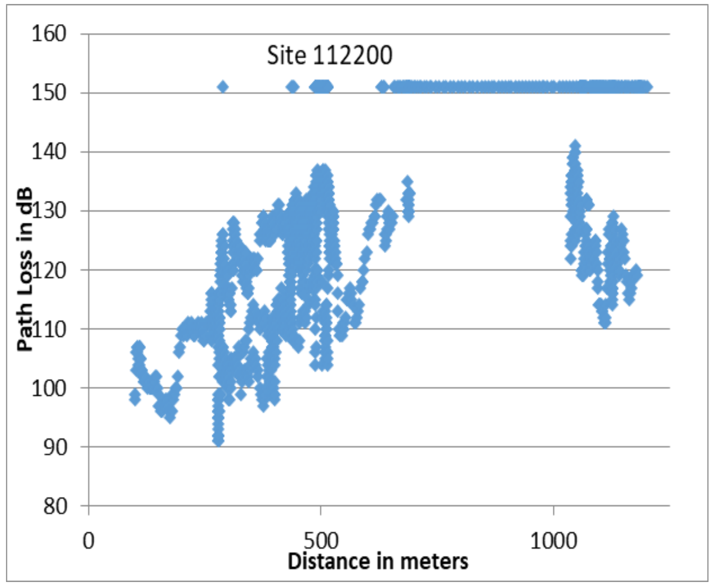

Site 111645
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200

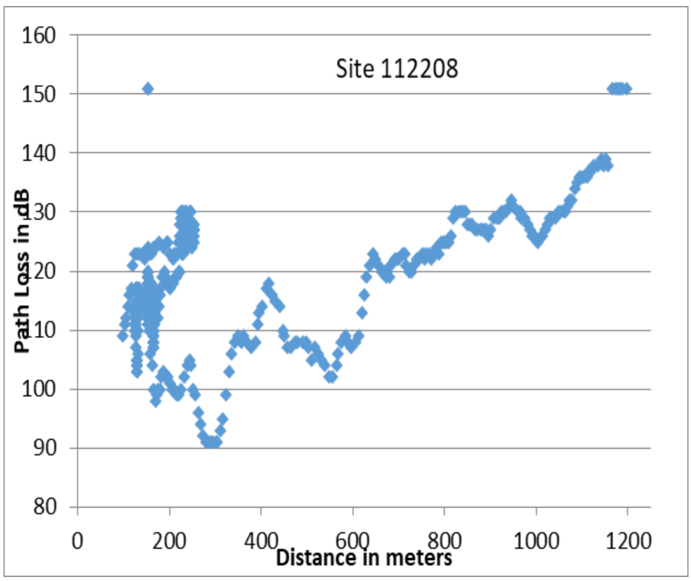

Site 111649 - S1
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
500
1000

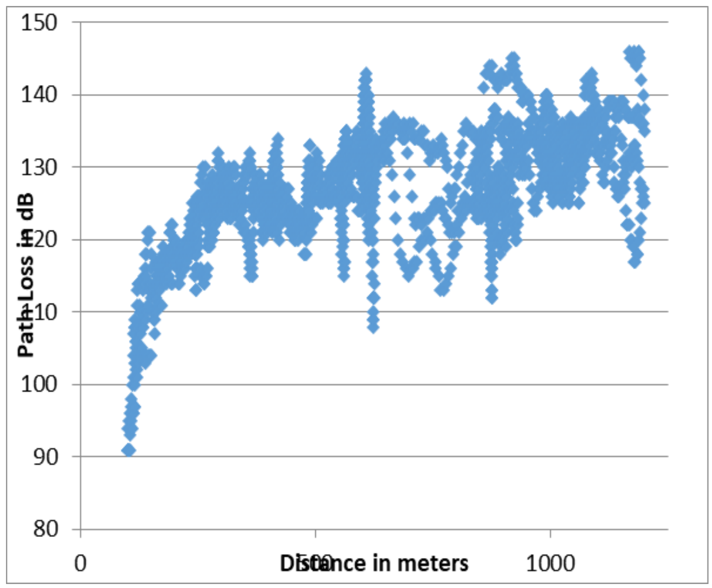

Site 111649 - S2
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200


Site 112166
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200


Site 112199
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200


Site 112200
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
500
1000


Site 112208
Path Loss in dB
Distance in meters
160
150
140
130
120
110
100
90
80
0
200
400
600
800
1000
1200


Path Loss in dB
Distance in meters
150
140
130
120
110
100
90
80
0
500
1000

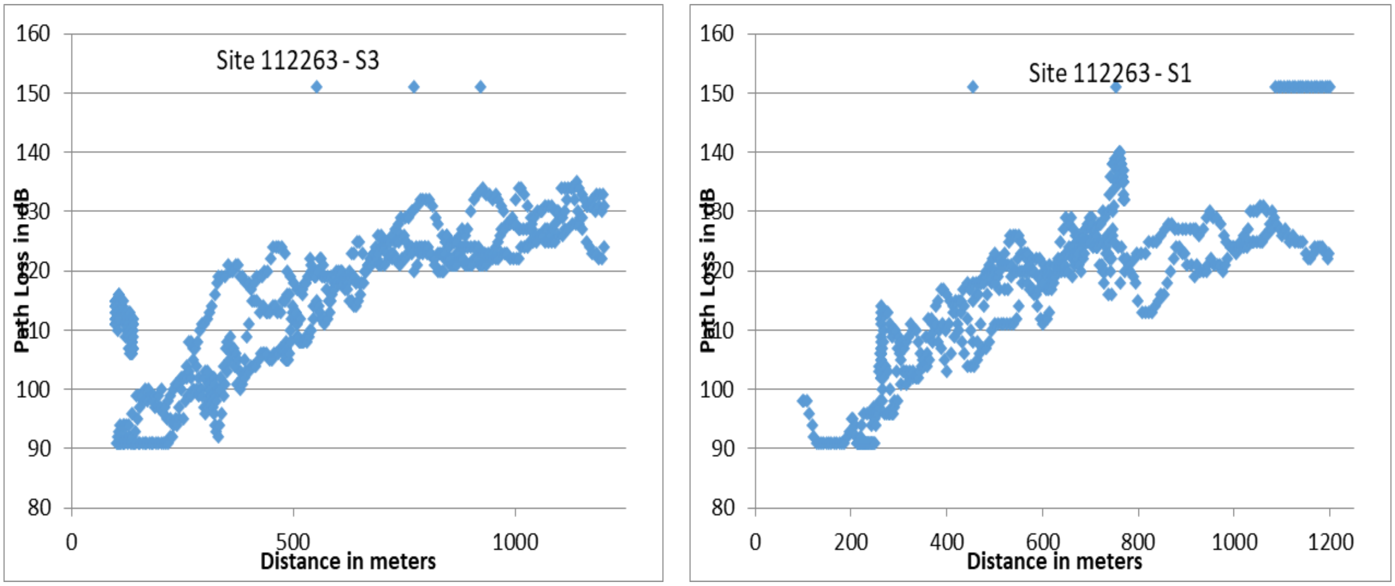
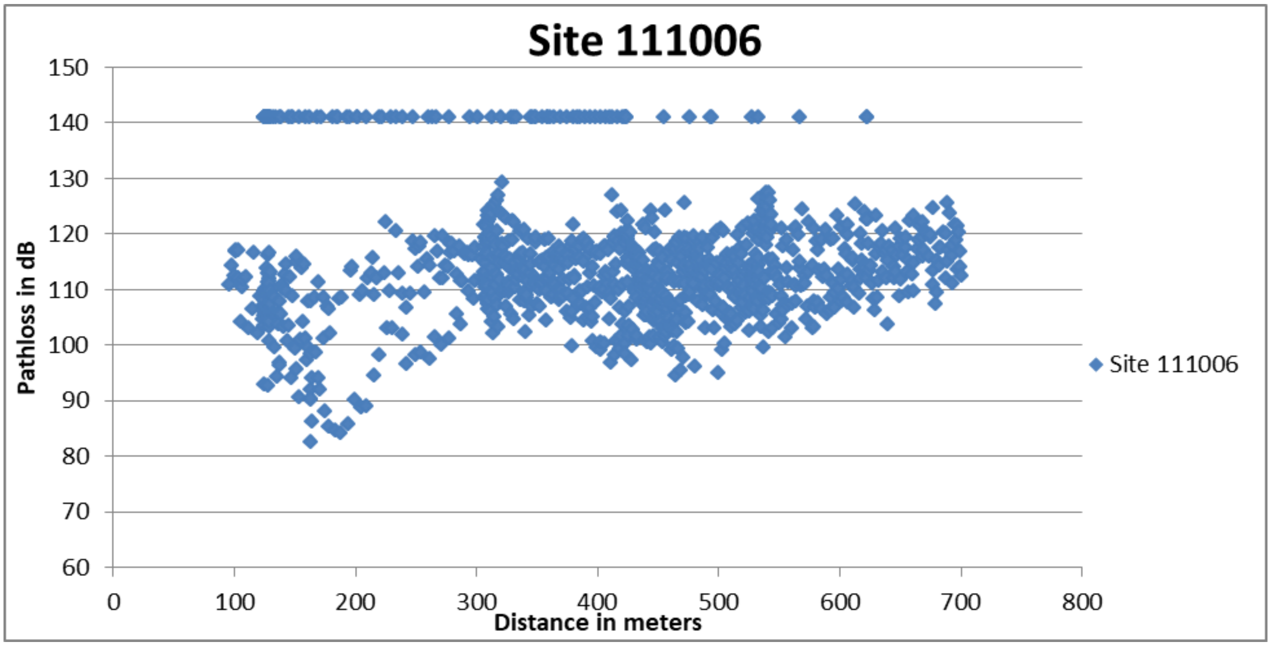


Figure 21 General trends of collected data for surveyed sites (1800MHZ)

As can be observed from Figure 18, there are some common features seen in almost all the sites. One is that an increase of path loss is seen in all the sites with distance. This is an expected result as is the case in all the propagation models (detailed in Sections 3.4 of chapter 3). The second one is that many sites have path loss records higher at the starting points than the subsequent areas. This is an indication of blockage in the closest points of the BS. The path loss begins to decrease roughly from 400m – 600 m from the BS. It can also be witnessed in most measurements that there is acceptable signal strength until around 800m from BS. At points greater than 800m from BS, there will begin to have no coverage points. The highest straight horizontal points in the figures indicate no coverage points (missing points during data collection) and are staffed by -108dB. This is due to the design of the BS (antenna height and down tilt angle).

The third one is that multiple values of signal strengths are measured at the same distance from the BS. This can happen because different interfering objects can encounter the signal at the same distance but different directions from BS and also different lobes (mail and side) are faced. The measured signal strength has therefore deterministic nature as it depends on different factors such as down tilt angle, height of BS antenna, environment and so on. We can make it somehow deterministic with some acceptable errors through fine tuning of path loss models.



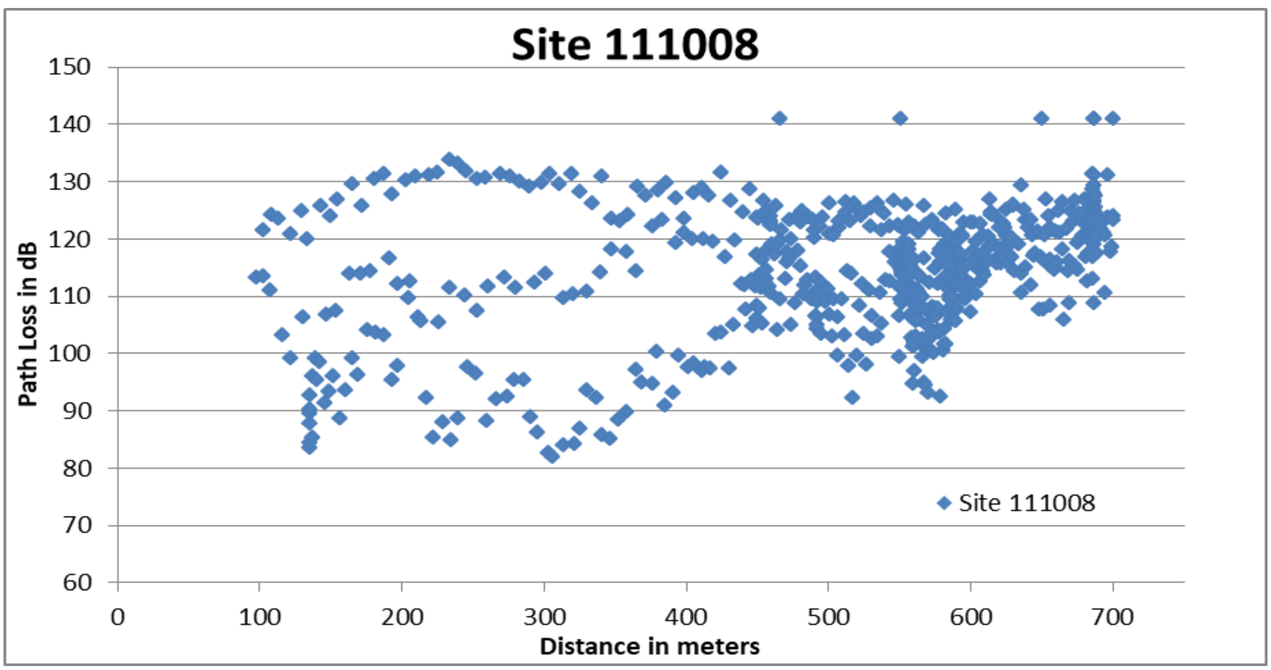


Figure 22 General trends of collected data for two surveyed sites (2100MHZ)

5.1.2. Data Trend on Average Values over +/- 5m and Performances

The measured values shown in the above section (section 5.1.1) are not suitable for analysis. Representative points are justified to be average values within +/-5m from the required distances as stated in the beginning part of this chapter. It is now required to see how the path loss models (SUI, ECC-33 and COST231) perform against these average measured values. RMSE, ME, SD and MAPE are used as a measure of error between the predicted values of the path loss models and the measured values. The table below shows the result in 23 sites from which measurement was taken. The urban, suburban and open model types of SUI, ECC-33 and COST231 are evaluated against the same site measurement.

BS ID	RMSE for COST 231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST 231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST 231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC	Area Type
111006													
	10.48	12.93	14.88	-5.84	-11.31	-0.07	8.98	6.27	10.95	6.90	8.02	9.68	Urban
	12.43	17.02	13.58	-8.88	-15.55	8.04	8.73	6.92	10.95	7.95	11.04	7.87	Suburban
	41.74	20.71		-0.82	-19.16		33.14	7.86		29.73	13.60		Open
111008													
	13.25	10.55	13.62	5.35	-0.13	1.11	18.23	10.55	13.58	10.13	7.46	9.77	Urban
	12.34	11.78	23.54	2.30	-4.37	19.22	16.13	10.94	13.58	9.04	7.40	17.58	Suburban
	32.02	14.03		-9.64	-7.97		23.90	11.54		22.99	8.24		Open
111010													
	10.53	12.37	13.63	-2.71	-8.18	-6.95	11.36	9.28	11.73	6.97	7.82	8.64	Urban
	11.69	15.59	16.20	-5.76	-12.42	11.17	10.37	9.41	11.73	7.29	9.79	10.77	Suburban
	39.04	18.77		-7.69	-16.03		30.86	9.76		28.02	11.72		Open
111036													
	10.60	12.74	13.32	-2.29	-7.77	-6.53	11.59	10.10	11.62	7.17	7.60	8.50	Urban
	11.64	15.64	16.41	-5.34	-12.01	11.59	10.58	10.03	11.62	7.21	9.50	10.77	Suburban
	38.68	18.61		-7.27	-15.61		30.74	10.13		27.81	11.77		Open

BS ID	RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST 231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST 231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC	Area Type
111054													
	11.96	14.68	15.85	-6.31	-11.78	-0.54	10.23	8.77	11.83	8.07	9.72	10.21	Urban
	13.81	18.41	14.05	-9.35	-16.02	7.57	10.26	9.07	11.83	8.97	11.82	8.36	Suburban
	42.52	21.85		-1.29	-19.63		34.36	9.60		29.91	13.93		Open
111058													
	7.10	9.87	10.08	-1.74	-7.22	-5.98	9.47	6.74	8.11	4.19	6.71	5.88	Urban
	8.38	13.20	14.60	-4.79	-11.46	12.13	7.73	6.55	8.11	4.90	9.23	9.92	Suburban
	37.37	16.45		-6.73	-15.06		28.56	6.62		27.80	11.55		Open
111098													
	16.02	21.75	19.44	-3.48	-18.95	-7.72	9.69	10.66	8.00	9.44	13.23	12.14	Urban
	18.66	25.22	8.01	-6.53	-23.19	0.40	11.36	9.91	8.00	11.40	16.16	4.57	Suburban
	49.23	28.32		-8.46	-26.80		39.57	9.15		33.76	18.63		Open
111100													
	7.32	6.97	7.17	3.65	-1.82	-0.58	13.81	6.72	7.15	5.36	4.28	4.40	Urban
	6.37	8.79	18.93	0.61	-6.06	17.53	11.25	6.37	7.15	4.28	5.19	14.52	Suburban
	31.96	11.50		-1.33	-9.67		22.83	6.23		24.74	7.51		Open

BTS ID	RMSE for COST 231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST 231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC	Area Type
111110													
	10.61	16.08	13.65	-7.61	-13.08	-11.85	7.50	9.35	6.79	6.66	9.55	8.70	Urban
	12.97	19.34	9.24	-0.65	-17.32	6.27	7.55	8.59	6.79	8.08	12.60	5.17	Suburban
	43.23	22.35		-2.59	-20.93		33.67	7.85		30.95	15.18		Open

111212													
	10.31	10.84	7.08	6.47	1.00	2.23	17.12	10.80	6.71	6.90	7.04	5.00	Urban
	8.73	10.36	21.43	3.43	-3.24	20.35	14.55	9.84	6.71	5.92	6.71	16.72	Suburban
	29.62	11.14		-8.51	-6.85		20.70	8.79		23.10	7.20		Open
111277													
	20.81	22.43	18.25	7.06	1.59	2.82	25.01	22.38	18.03	14.85	16.79	12.89	Urban
	19.99	21.61	27.63	4.02	-2.65	20.94	23.27	21.44	18.03	14.39	15.87	19.94	Suburban
	34.10	21.33		-7.92	-6.26		27.03	20.39		21.92	15.06		Open
111577													
	6.99	9.87	7.25	1.01	-4.46	-3.22	11.91	8.81	6.49	4.69	6.07	4.53	Urban
	7.21	11.86	16.24	-2.03	-8.70	14.89	9.64	8.05	6.49	4.60	7.38	11.90	Suburban
	34.67	14.33		-3.97	-12.31		25.45	7.33		26.35	9.51		Open

BTS ID	RMSE for COST 231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST 231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC	Area Type
111579 – S1													
	12.05	9.89	10.63	7.26	1.79	3.03	18.71	9.72	10.18	9.39	6.92	7.53	Urban
	10.49	9.84	23.47	4.22	-2.45	21.14	16.23	9.53	10.18	7.95	5.73	18.40	Suburban
	29.34	11.26		-7.72	-6.06		20.51	9.49		22.21	6.00		Open
111579 – S2													
	13.01	16.32	14.27	-3.03	-8.51	-7.27	14.19	13.93	12.28	7.64	8.45	8.75	Urban
	14.04	18.50	16.38	-6.08	-12.75	10.85	13.08	13.41	12.28	7.95	10.46	10.88	Suburban
	40.07	20.85		-8.02	-16.35		30.38	12.93		28.09	12.56		Open
111645													
	15.42	14.46	12.29	9.93	4.45	5.69	22.32	13.75	10.89	10.70	8.99	8.46	Urban
	13.66	13.04	26.18	6.88	0.21	23.80	19.85	13.04	10.89	8.96	7.92	20.68	Suburban
	27.70	12.76		-5.06	-3.39		19.25	12.30		20.46	8.75		Open
111649 - S1													
	17.59	15.26	13.08	15.01	9.54	10.77	25.66	11.91	7.41	14.53	12.27	10.50	Urban
	15.07	12.17	29.82	11.97	5.30	28.89	22.90	10.96	7.41	12.33	9.09	25.49	Suburban

	21.97	10.07		-9.97	1.69		13.68	9.92		17.26	6.89		Open
111649 - S2													
	16.15	13.57	12.82	12.41	6.94	8.17	23.33	11.67	9.88	12.28	10.48	9.76	Urban
	13.95	11.44	28.08	9.37	2.70	26.29	20.71	11.12	9.88	10.66	8.60	23.31	Suburban
	24.83	10.65		-2.57	-0.91		16.82	10.62		18.83	7.45		Open
112166													
	20.75	17.16	16.79	18.26	12.79	14.03	28.49	11.45	9.23	17.22	14.22	14.20	Urban
	18.12	13.79	33.44	15.22	8.55	32.14	25.71	10.81	9.23	15.02	11.60	29.66	Suburban
	19.40	11.34		-6.72	4.94		12.34	10.21		14.65	9.59		Open

BS ID	RMSE for COST 231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST 231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC	Area Type
112199													
	13.73	10.52	9.83	12.48	7.01	8.25	21.65	7.85	5.35	10.80	8.00	7.43	Urban
	11.04	7.54	26.90	9.44	2.77	26.36	18.80	7.01	5.35	8.43	5.42	22.86	Suburban
	23.22	6.26		-22.50	-0.84		14.49	6.20		19.18	4.43		Open
112200													
	10.91	11.18	13.15	-0.07	-5.54	-4.30	13.53	9.71	12.42	7.56	6.70	8.15	Urban
	11.35	13.96	18.58	-3.11	-9.78	13.81	12.02	9.96	12.42	7.04	7.94	12.96	Suburban
	36.71	16.96		-35.05	-13.39		28.39	10.42		26.46	10.04		Open
112208													
	14.34	12.28	11.38	10.24	4.77	6.01	21.30	11.31	9.67	10.75	9.57	7.81	Urban
	12.35	10.79	25.99	7.20	0.53	24.12	18.73	10.77	9.67	9.18	7.38	21.13	Suburban
	26.70	10.74		-24.74	-3.08		18.38	10.29		20.29	6.89		Open
112263 - S1													
	13.45	8.58	10.86	12.01	6.54	7.78	21.09	5.56	7.58	10.81	6.72	8.50	Urban
	10.82	5.91	26.98	8.97	2.30	25.89	18.26	5.45	7.58	8.47	4.48	23.03	Suburban
	23.76	5.80		-22.97	-1.31		15.26	5.65		19.27	4.07		Open
112263 - S3													
	13.62	9.66	9.82	12.89	7.42	8.66	22.00	6.19	4.63	11.55	7.75	7.79	Urban
	10.79	6.26	27.17	9.85	3.18	26.77	19.09	5.40	4.63	9.17	4.33	23.36	Suburban

	22.52	4.72		-22.09	-0.43		13.37	4.70		18.91	2.20		Open

Table 6 Performances of SUI, ECC-33 and COST231 path loss models (1800MHZ).

Based on the above table, there are some observations we can make. In the table, mainly an RMSE and MAPE are used to measure the closeness of the path loss models to the measured data. The least value being highest closeness of the path loss models to the measured data. The urban type of the three models is evaluated in the first rows of the table. The second rows compare the suburban type of the models to the measured values and the third to open area type. Area classification or morphology type is done based the closeness of the area type models (Urban, Suburban and Open) to the measured data. ME and SD are also calculated to see distribution of the error.

Among the 23 sites evaluated, 12 have fallen into urban type, 4 have fallen into suburban type and 7 into an open type. The RMSE value of the models under urban type is in the range from 6.99dB to 18.25dB. COST231 has performed best in 8 sites out of 12 that are labelled urban which represents 66.67% of the total sites. ECC-33 has performed best in 3 sites and SUI in 1 site which is 25% and 8.33% of the sites labelled urban respectively. COST231 has outsmarted the other models in urban areas and has scored a minimum value of 6.99dB and a maximum value of 13dB RMSE.

Among the four sites whose measured data are classified to have come from suburban area, ECC-33 has performed best for 2 sites which is 50% of the suburban sites; COST231 and SUI have performed best in one site each. The RMSE value of ECC-33 is around 9dB which is an acceptable value to use it without tuning. The remaining 7 sites are labelled open based on the closeness of the open type model to the measured data of these sites. In all the 8 sites the minimum RMSE is scored exceptionally by SUI. This covers 100% of the sites. The minimum RMSE scored by SUI in the open areas is 4.72dB and the maximum one is 11.34dB which is a good value of RMSE before tuning.

Similarly, among the 25 sites in 2100MHZ, 6 of them have their measured data classified under urban category based on the path loss models. 9 of them are suburban and 10 sites are under open area category. SUI and ECC-33 have outperformed equally in 3 sites each under urban areas.. SUI is found to be best in 8 of the 9 sites under suburban areas(i.e. 89%) and is also best in all the areas under open category (100%).. The RMSE value of ECC-33 ranges from 5.44dB – 8.6dB and ECC-33 with a range of 5.9dB – 13.52dB in urban area sites. For suburban areas, SUI is the best performer with 89% performance & an RMSE value of ranging from 4.56dB – 20.68dB and SUI with 100% best performance has an RMSE range from 6.28dB – 15.67dB. Table 8 shows the detail.

BTS ID	RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST 231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC	Area Type
111006	15.21	13.08	11.60	11.90	3.38	9.34	9.48	12.63	6.88	11.42	10.32	8.61	Urban
	12.97	11.63	28.66	8.85	-0.04	27.83	9.48	11.63	6.88	9.83	9.28	24.54	Suburban
	25.77	10.78	28.66	-23.96	-2.82	27.83	9.48	10.40	6.88	21.00	8.14	24.54	Open
111008													
	14.56	11.33	11.20	12.26	3.75	9.70	7.85	10.70	5.60	12.14	8.93	9.38	Urban
	12.11	9.78	28.74	9.21	0.32	28.19	7.85	9.77	5.60	9.85	7.08	24.98	Suburban
	24.87	9.00	28.74	-23.60	-2.46	28.19	7.85	8.66	5.60	20.82	5.42	24.98	Open
111010													
	10.52	5.44	9.99	8.41	-0.11	5.84	6.32	5.44	8.11	7.94	4.09	7.24	Urban
	8.28	6.56	25.65	5.36	-3.53	24.33	6.32	5.53	8.11	6.11	4.55	21.90	Suburban
	28.17	8.64	25.65	-27.46	-6.32	24.33	6.32	5.89	8.11	23.19	6.23	21.90	Open
111036													
	14.56	8.60	15.17	9.30	0.78	6.74	11.21	8.56	13.59	11.94	6.97	12.87	Urban
	11.28	9.49	25.43	6.25	-2.64	25.22	11.21	9.36	13.59	10.95	6.80	24.41	Suburban
	28.83	11.72	28.65	-26.56	-5.42	25.22	11.21	10.39	13.59	21.86	7.82	24.41	Open
111054													
	12.14	9.98	9.17	9.63	1.12	7.07	7.38	9.92	5.84	9.69	7.57	7.38	Urban
	9.89	8.96	25.01	6.58	-2.31	25.56	7.38	9.07	5.84	7.84	6.19	22.24	Suburban
	27.25	9.55	26.22	-26.23	-5.09	25.56	7.38	8.08	5.84	22.62	5.64	22.24	Open
111058-s1													
	13.21	15.60	10.02	5.18	-3.34	2.61	12.15	15.24	9.67	10.07	11.43	7.64	Urban
	11.32	13.17	23.15	2.13	-6.76	21.10	12.15	14.26	9.67	9.42	10.87	17.82	Suburban
	33.00	16.17	23.21	-30.69	-9.55	21.10	12.15	13.05	9.67	25.19	10.14	17.82	Open
111058-													

s3													
	15.95	9.90	13.51	14.83	6.31	12.26	5.89	7.62	5.68	13.59	7.82	11.52	Urban
	13.08	7.32	30.03	11.78	2.89	30.75	5.89	6.96	5.68	10.93	5.77	28.22	Suburban
	21.85	6.28	31.27	-21.04	0.10	30.75	5.89	6.28	5.68	18.98	4.45	28.22	Open
111100													
	21.48	16.07	20.30	15.53	7.01	12.96	14.84	14.46	15.61	19.07	13.73	18.48	Urban
	19.28	14.89	33.90	12.48	3.59	31.45	14.84	14.50	15.61	17.22	12.67	31.47	Suburban
	25.17	14.67	35.12	-20.33	0.81	31.45	14.84	14.65	15.61	17.11	11.81	31.47	Open
111110													
	15.41	8.55	13.96	13.62	5.10	11.05	7.21	6.86	8.53	12.95	6.27	10.90	Urban
	12.62	6.93	29.32	10.57	1.68	29.54	7.21	6.81	8.53	10.19	5.16	27.64	Suburban
	23.38	7.04	30.75	-22.24	-1.10	29.54	7.21	6.95	8.53	19.53	5.65	27.64	Open
111212													
	13.79	10.60	10.48	11.70	3.18	9.14	7.30	10.11	5.14	11.20	8.28	8.45	Urban
	11.03	6.60	27.79	8.65	-0.24	27.62	7.30	9.19	5.14	8.97	6.18	24.35	Suburban
	25.24	8.64	28.10	-24.16	-3.02	27.62	7.30	8.09	5.14	21.24	5.11	24.35	Open
111277													
	11.78	8.84	8.84	10.13	1.62	7.57	6.02	8.69	4.56	8.77	6.86	6.65	Urban
	9.33	7.21	25.48	7.08	-1.81	26.06	6.02	7.80	4.56	6.41	6.02	22.70	Suburban
	26.42	8.16	26.45	-25.73	-4.59	26.06	6.02	6.75	4.56	22.37	6.05	22.70	Open
111577													
	7.12	10.60	5.90	2.46	-6.06	-0.10	6.68	8.69	5.90	4.70	7.40	4.09	Urban
	6.45	10.99	18.68	-0.59	-9.48	18.38	6.68	7.97	5.90	4.69	8.59	15.21	Suburban
	34.06	14.21	19.31	-33.40	- 12.26	18.38	6.68	7.18	5.90	27.12	9.92	15.21	Open
111579 - S1													
	10.56	8.33	9.06	7.48	-1.04	4.91	7.45	8.27	7.62	8.36	4.15	6.43	Urban
	7.68	4.56	24.47	4.43	-4.46	23.40	7.45	7.87	7.62	6.49	4.93	20.60	Suburban
	29.34	10.47	24.61	-28.38	-7.24	23.40	7.45	7.56	7.62	23.83	6.70	20.60	Open
111579 - S2													
	17.30	10.52	15.01	16.10	7.58	13.53	6.34	7.30	6.50	15.12	9.00	12.94	Urban
	14.53	7.02	31.97	13.05	4.16	32.02	6.34	6.85	6.50	12.42	6.56	29.96	Suburban
	20.76	6.61	32.67	-19.77	1.37	32.02	6.34	6.47	6.50	17.91	5.06	29.96	Open
111632													
	17.64	14.10	14.09	14.93	6.41	12.36	9.41	12.55	6.76	14.64	11.30	11.55	Urban
	15.00	10.35	31.24	11.88	2.99	30.85	9.41	11.55	6.76	12.71	9.29	27.94	Suburban
	22.95	10.33	31.58	-20.94	0.20	30.85	9.41	10.33	6.76	18.85	7.61	27.94	Open
111645													
	21.52	14.30	18.79	21.10	12.59	18.54	4.21	6.80	3.06	20.21	12.16	17.90	Urban
	18.32	10.92	35.80	18.05	9.16	37.03	4.21	5.91	3.06	17.28	9.22	35.66	Suburban

	15.35	8.04	37.15	-14.76	6.38	37.03	4.21	4.89	3.06	14.24	6.78	35.66	Open
111649 - S1													
	27.29	26.69	23.64	15.09	6.57	12.52	22.74	25.87	20.06	23.72	21.81	20.49	Urban
	23.54	20.68	36.81	12.04	3.15	31.01	22.74	24.87	20.06	21.97	20.01	31.94	Suburban
	30.80	23.66	36.93	-20.78	0.36	31.01	22.74	23.65	20.06	16.68	18.23	31.94	Open
111649 - S2													
	12.72	11.74	9.79	8.55	0.03	5.98	9.42	11.74	7.75	10.15	7.97	7.74	Urban
	10.17	8.46	25.52	5.50	-3.39	24.47	9.42	10.95	7.75	8.51	6.79	21.30	Suburban
	28.89	11.80	25.67	-27.31	-6.18	24.47	9.42	10.05	7.75	23.16	6.85	21.30	Open
111708 - S1													
	9.55	12.81	11.36	-0.60	-9.11	-3.16	9.53	9.00	10.91	6.68	9.31	7.87	Urban
	8.07	15.29	13.28	-3.65	-12.53	15.33	9.53	9.05	10.91	7.52	11.21	13.73	Suburban
	37.68	17.90	18.81	-36.46	-15.32	15.33	9.53	9.26	10.91	28.38	13.12	13.73	Open
112166													
	12.08	7.49	12.57	7.62	-0.90	5.05	9.37	7.43	11.52	8.20	6.04	9.32	Urban
	9.89	9.11	24.05	4.57	-4.32	23.54	9.37	7.96	11.52	7.55	7.14	21.97	Suburban
	29.76	11.25	26.21	-28.25	-7.11	23.54	9.37	8.72	11.52	23.28	8.20	21.97	Open
112199													
	13.30	10.65	11.27	9.60	1.08	7.03	9.21	10.60	8.81	10.62	7.96	9.28	Urban
	11.31	9.91	25.90	6.55	-2.34	25.52	9.21	10.06	8.81	8.66	7.07	22.70	Suburban
	27.83	10.81	27.00	-26.27	-5.13	25.52	9.21	9.52	8.81	22.42	6.68	22.70	Open
112200													
	15.41	14.75	13.52	8.06	-0.46	5.50	13.14	14.74	12.36	12.64	10.27	11.31	Urban
	13.86	14.68	25.26	5.01	-3.88	23.99	13.14	14.17	12.36	11.43	9.06	21.58	Suburban
	30.75	15.10	26.98	-27.80	-6.66	23.99	13.14	13.55	12.36	23.06	8.40	21.58	Open
112208													
	23.48	19.42	20.56	18.33	9.82	15.77	14.68	16.76	13.20	21.25	15.68	18.69	Urban
	21.14	17.18	35.68	15.28	6.39	34.26	14.68	16.06	13.20	18.71	12.87	34.07	Suburban
	22.86	15.67	36.71	-17.53	3.61	34.26	14.68	15.25	13.20	15.49	10.44	34.07	Open
112263 - S1													
	19.55	14.37	16.29	17.79	9.27	15.22	8.12	10.98	5.80	17.47	12.27	14.57	Urban
	16.63	9.71	33.95	14.74	5.85	33.71	8.12	10.05	5.80	15.05	9.56	31.40	Suburban
	19.82	9.45	34.20	-18.08	3.06	33.71	8.12	8.94	5.80	16.74	7.23	31.40	Open
112263 - S3													
	19.41	13.09	16.69	18.06	9.54	15.50	7.11	8.96	6.21	17.53	11.63	14.88	Urban

	16.55	8.84	34.14	15.01	6.12	33.99	7.11	8.28	6.21	15.10	8.95	32.18	Suburban
	19.17	8.26	34.55	-17.80	3.34	33.99	7.11	7.56	6.21	16.42	6.56	32.18	Open

Table 7 Performance result of sites (2100MHZ)

The most often used words here in this thesis and probably other similar area researches would probably be urban, suburban and rural (open). Path loss models even define particular parameter values based on these area types. The words could be easy to understand from other discipline perspective but not that easy from the perspective of path loss models. Almost all models use the words without properly defining them. So what do we mean when we say

BTS ID	Sector ID	Azimuth	Height(m)	Total Downtilt	Area Type	Environmental profile
111006	D2	60	26	7	Urban	there are buildings of almost the same height as antenna height, many buildings, downs and ups terrain, high traffic area, lots of trees, narrow and bending roads
111008	D2	340	24	6	Urban	very narrow and bending roads, medium buildings, downs and ups terrain, short antenna height
111010	D1	320	24	6	Urban	short antenna height, downs and ups terrain, high traffic area, proportional building heights as antenna height
111036	D1	90	25	16	Urban	narrow and bending roads, downs and ups terrain, lots of trees, some buildings of the same height as antenna height, high down tilt angle
111054	D1	110	20	18	Urban	antenna height is high, dense big buildings comparable to antenna height, very high traffic, narrow and bending roads, big tilt angle
111058	D1	30	21	13	Urban	high density of high rising buildings (5 floors and above), narrow and bending roads, high traffic area, short antenna height, high down tilt angle
111212	D2	330	34	4	Urban	medium traffic area, buildings are comparable to antenna height, medium antenna height, up and down terrain,
111277	D3	245	25	5	Urban	wide and straight roads, bridge roads, heavy traffic, higher building size than antenna height, low antenna height
111577	D3	185	27.5	3	Urban	many medium and some high buildings, high traffic, a little sloppy terrain
111579	D2	170	27.5	8	Urban	narrow and bending roads, up and down terrain, low traffic, many small and medium size buildings, some high buildings
111645	D2	0	30.5	5	urban	medium antenna height, small tilt angle, wide roads, heavy traffic, many medium and high buildings, lots of trees
112200	D1	320	32	7	urban	roadside site, wide and straight road, low traffic, many ground living villas, medium antenna height, up and down terrain, site is at higher ground, some open spaces

urban, suburban and open? In an intuitive understanding, urban is an area of highest path loss compared to the other areas, suburban is of medium path loss and open is the one that has minimum path loss. This is determined only after field data measurement and evaluating the data against the path loss models. But what if we want to go in the reverse order, i.e, defining the area type and then determining what area type model we have to use. In this thesis we have identified three area types as per the analysis on table 15. The three area types as per the observation from the environment have been defined below for each site.

The sites listed in Table 6 have common environmental profile. These sites are actually labelled urban by the path loss models not only due to their environmental profile. Antenna height, down tilt angle and azimuth angle can also contribute to the labelling in a way these parameters have their influence on the measured data. So, urban area in this thesis is defined as an area with high traffic flow. There can be considerable traffic flow even in the inner access roads. It is also known by its relatively high buildings (5 floors and above) placed in close proximity. Mostly they have either narrow & bending roads (14m wide and below) or a wide bridge road with subways. The terrain profile of urban areas is up and down leaving coverage holes in some areas.

The table below shows the environmental profile of suburban areas.

BTS ID	Sector ID	Azimuth	Height(m)	Total Downtilt	Area Type	Environmental profile
111098	D3	200	28	10	Suburban	wide roads, buildings of small size and spaced apart, no heavy traffic, more living houses of ground and G+1 types, fairly flat terrain
111100	D1	10	25	4	Suburban	a little slopy terrain, mostly ground living villas, some buildings, wide and bending roads, medium antenna height
111110	D3	0	22	7	Suburban	small antenna height, mostly ground living villas, few buildings, wide roads, medium traffic, a little

						sloppy terrain
111579	D1	10	27.5	18	Suburban	some medium and small buildings, many ground villas, small and bending roads, a little slopy terrain, small traffic

Table 8 Suburban area sites' environmental profile with design parameters

Suburban area in this thesis is defined as an area having some numbers of medium buildings (4 floors and below) spaced fairly. There are a lot of ground living villa houses and a one or two living buildings. In these areas, there is no much traffic flow compared to the urban areas. The roads in these areas are wide and bending. A sloppy and plain terrain profile is one feature which can identify suburban areas.

The third category of area classification is an open area. The environmental profiles of sites under this category are listed in the table below.

BS ID	Sector ID	Azimuth	Height(m)	Total Down tilt	Area Type	Environmental profile
111649	D1	60	32	7	Open	roadside site, very wide and straight road, low traffic, up and down terrain, high antenna height, site is at higher ground, medium buildings distanced apart, presence of open areas
111649	D2	100	32	8	Open	roadside site, very wide and straight road, low traffic, up and down terrain, high antenna height, site is at higher ground, medium buildings distanced apart, presence of open areas
112166	D2	350	32	5	Open	roadside site, very wide and straight road, few medium height buildings, site is at higher ground, high antenna height, many ground living villas, presence of open areas, slopy but plain terrain
112199	D3	0	42	5	Open	highest antenna height, many open spaces, narraw and bending roads, few buildings, many ground villa houses, very low traffic, slopy but plain terrain, fairly upright antenna

112200	D1	320	32	7	Open	roadside site, wide and straight road, low traffic, many ground living villas, medium antenna height, up and down terrain, site is at higher ground, some open spaces
112263	D1	10	33	4	Open	very wide and straight roads, medium antenna height, slopy but plain terrain, site is at higher ground, some small height shadows, ample open spaces, no traffic, no living houses, very few medium buildings
112263	D3	240	33	14	Open	very wide and straight roads, medium antenna height, up and down terrain, site is at higher ground, some small height shadows, ample open spaces, no traffic, no living houses, very few medium buildings

Table 9 Open area sites' environmental profile with design parameters

As can be learned from table 8, Open areas can be identified with the following environmental profiles. Open areas have wide and straight roads on which there is only low traffic flow. These areas have a lot of open spaces. Only very few buildings exist in these areas and they are mostly covered by ground living villas. The terrain profiles of such areas could be flat or sloppy & plain.

The general trends of the measured data in the three area types are shown in the figures below.

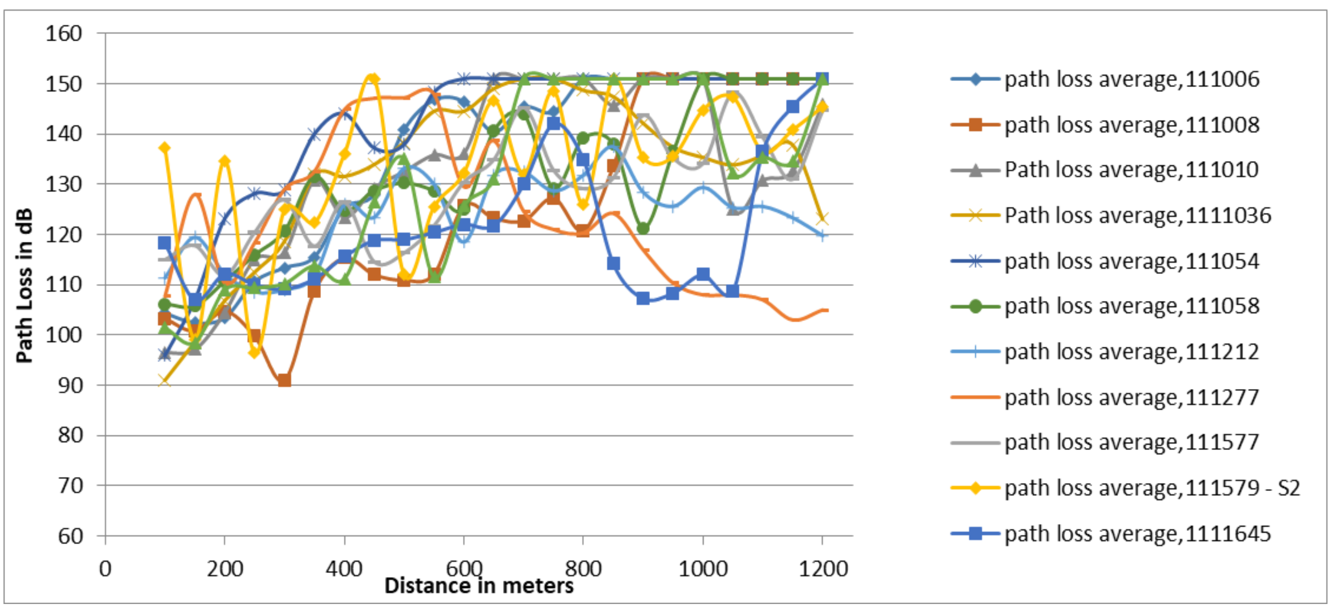


Figure 23 General trends of collected data at selected distances for urban area sites (1800MHZ)

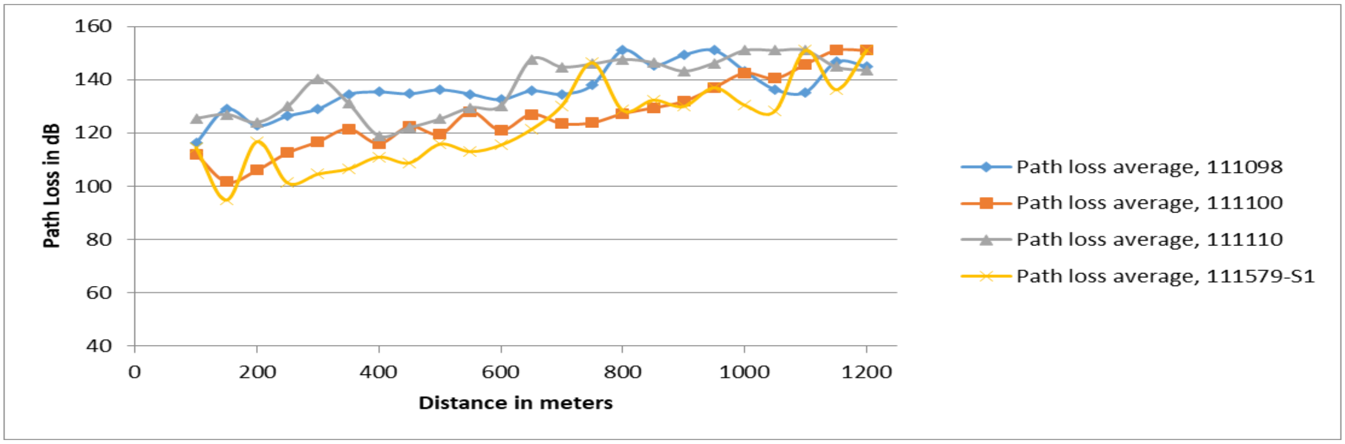


Figure 24 General Trends of collected data at selected distances for Suburban area sites (1800MHZ)

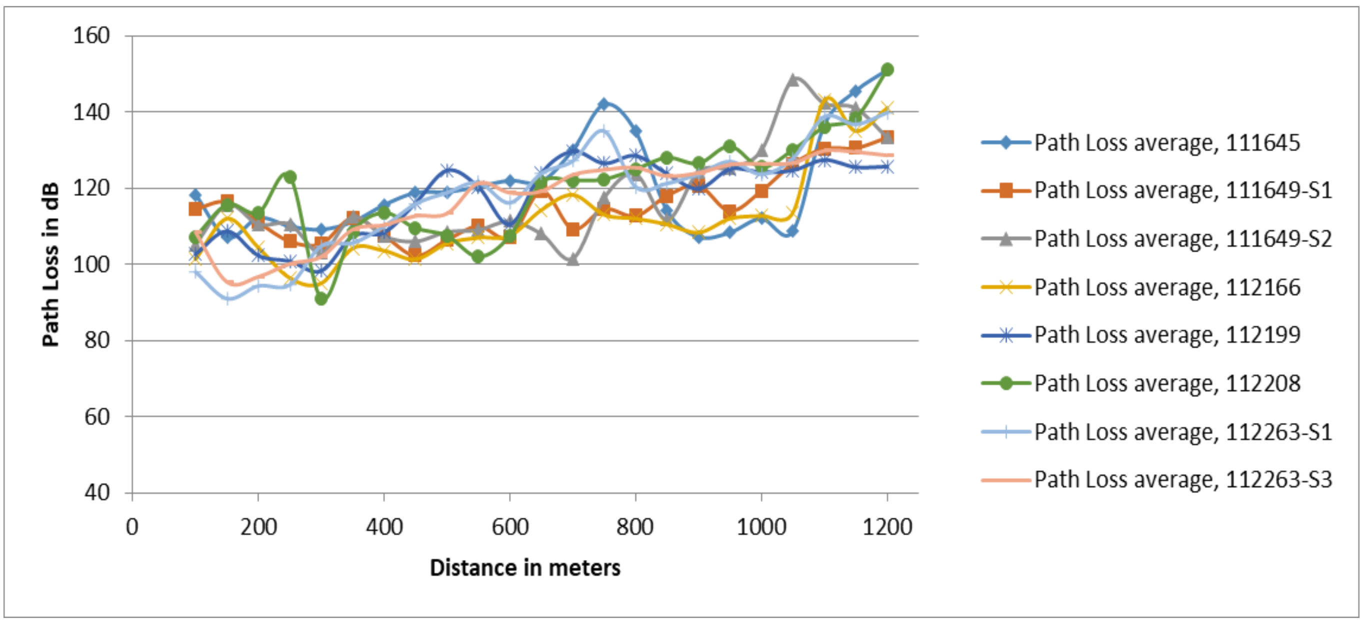


Figure 25 General trends of collected data at selected distances for open area sites

Evaluating the path loss models against the average path loss calculated from the average measured path loss values of each urban site will result in an RMSE value of 3.27dB for COST231, which is the least value compared to the other two models. COST231 scores an RMSE of 5.73dB over the overall average path loss values of suburban area sites and SUI is 6.0dB for the open area sites. Figure 22, 23 and 24 shows the graph of the overall average path loss with distance.

RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST231	MAPE for SUI	MAPE for ECC
3.27	7.12	6.07	0.14	0.31	0.26	0.08	0.12	0.11	2.15	4.75	4.07

Table 10 COST231 Urban performance over overall averaged

MSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST231	MAPE for SUI	MAPE for ECC
5.73	11.47	13.78	-3.86	-3.98	13.07	6.50	10.75	4.37	3.67	5.53	10.26

Table 11 COST231 Suburban performance over overall averaged

RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST231	MAPE for SUI	MAPE for ECC
22.35	6.00	27.67	-21.65	0.01	27.21	13.51	6.00	5.03	18.60	4.04	23.72

Table 12 SUI open performance over overall averaged

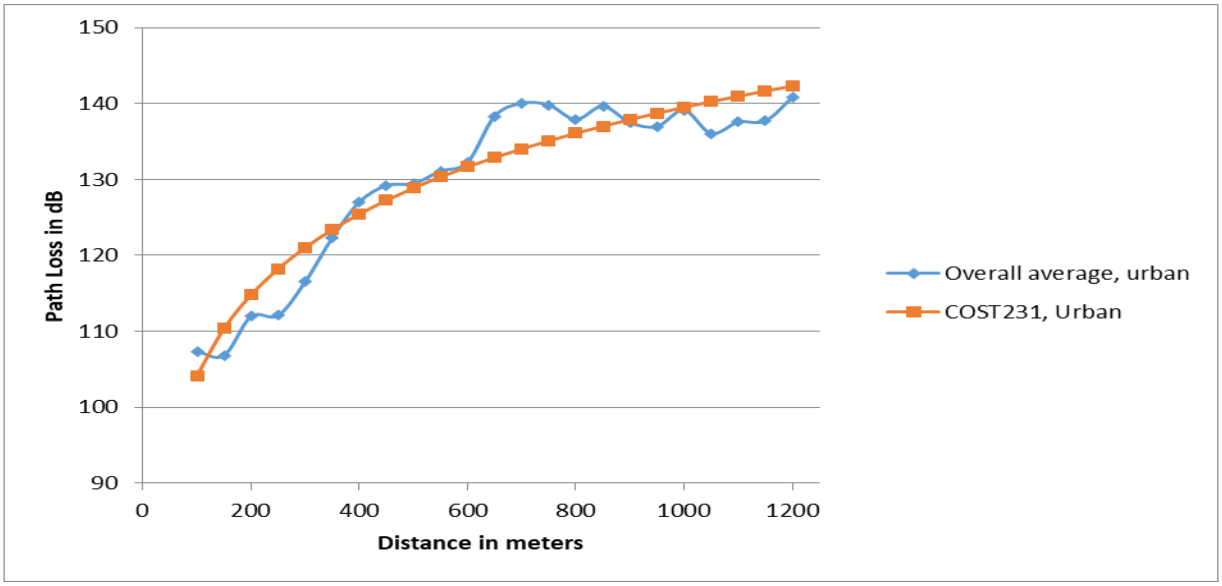


Figure 26 Path Loss for overall average value of urban area sites and COST231 empirical model (1800MHZ)

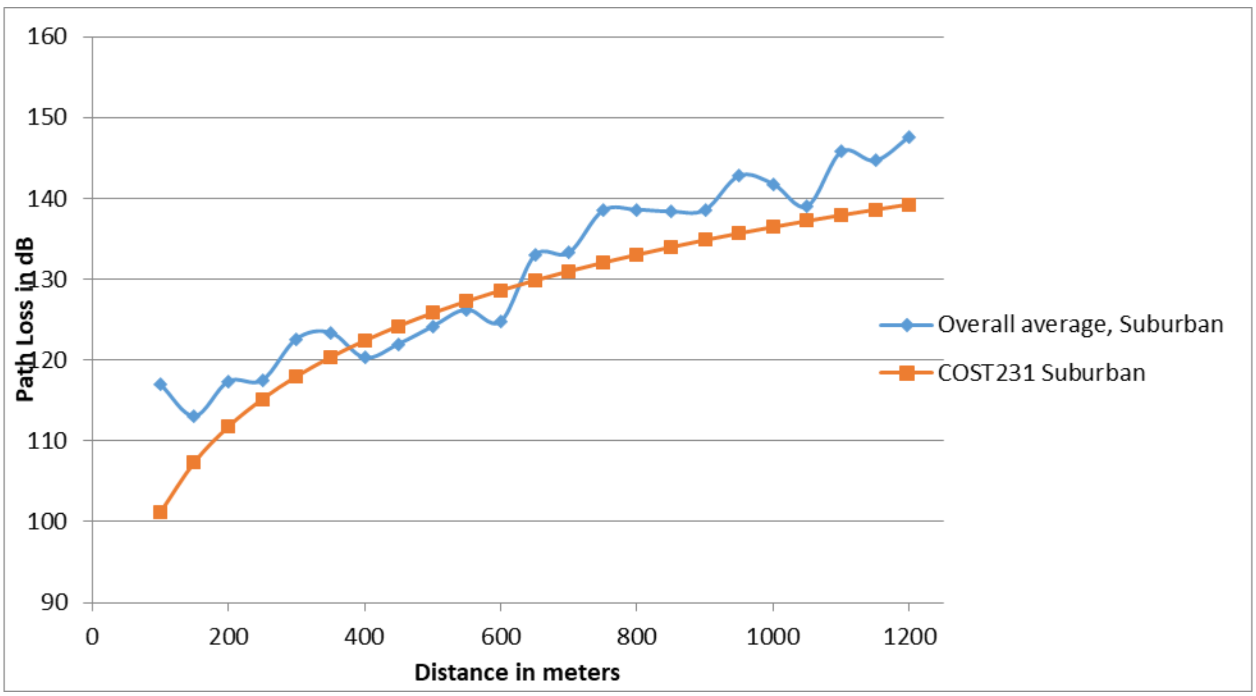


Figure 27 Path Loss for overall average value of suburban area sites and COST231 empirical model (1800MHZ)

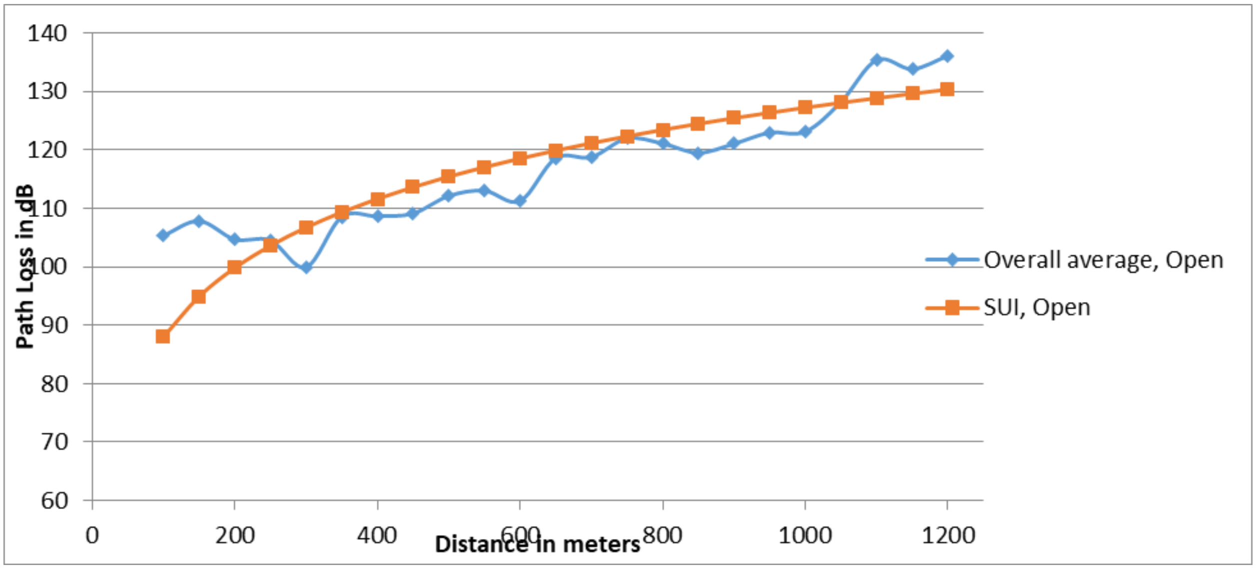


Figure 28 Path Loss for overall average value of open area sites and SUI empirical model (1800MHZ)

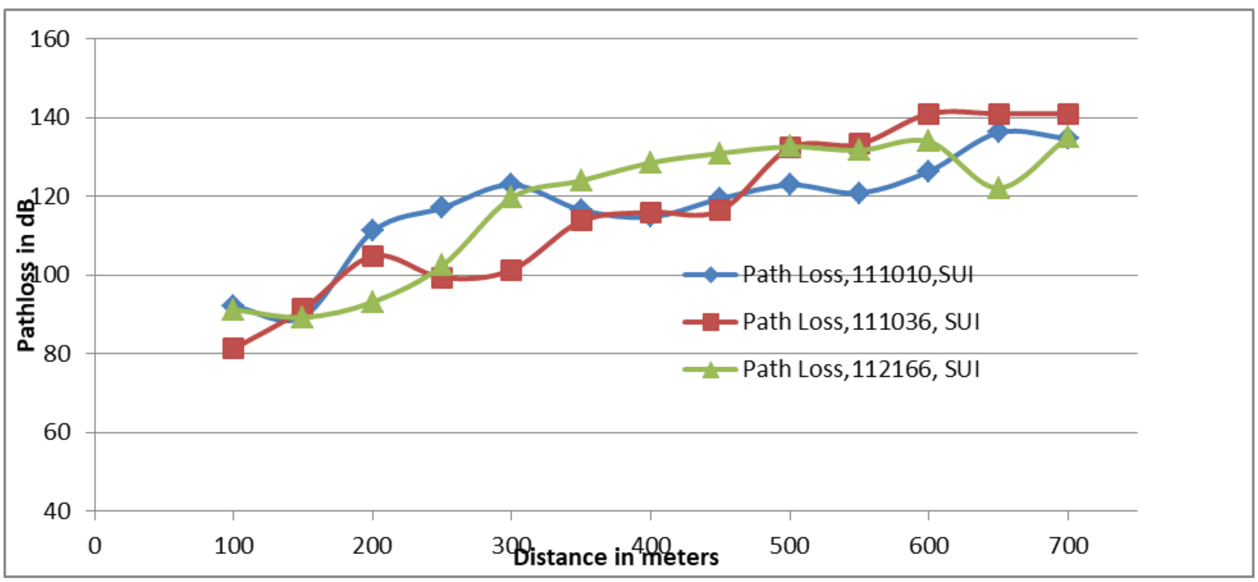


Figure 29 General Trends of collected data at selected distances for some urban area sites (2100MHZ)

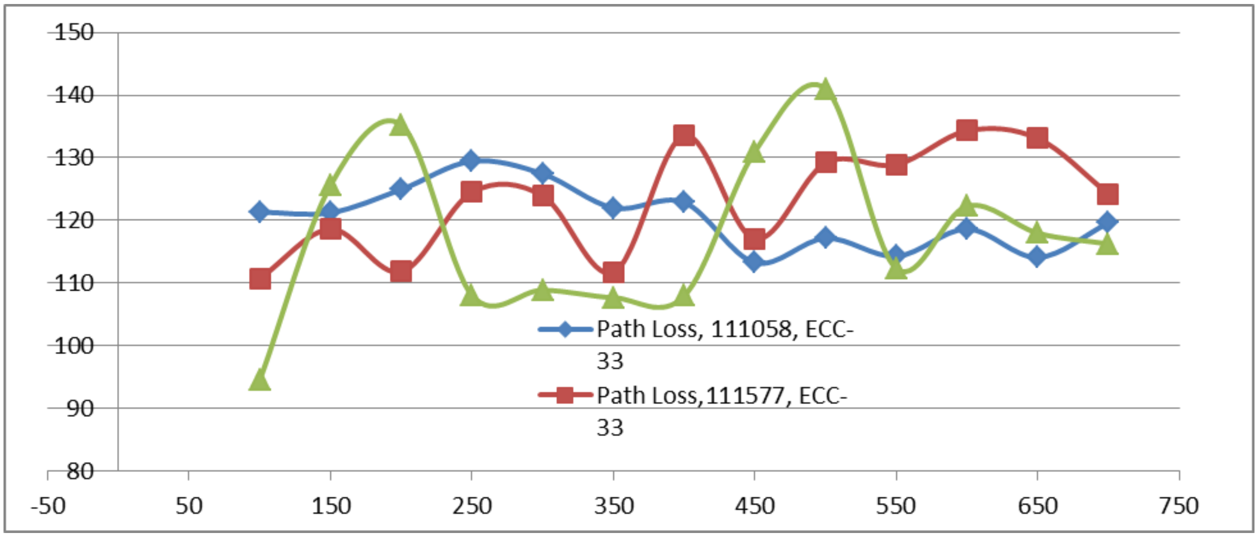


Figure 30 General Trends of collected data at selected distances for Urban area sites (2100MHZ)

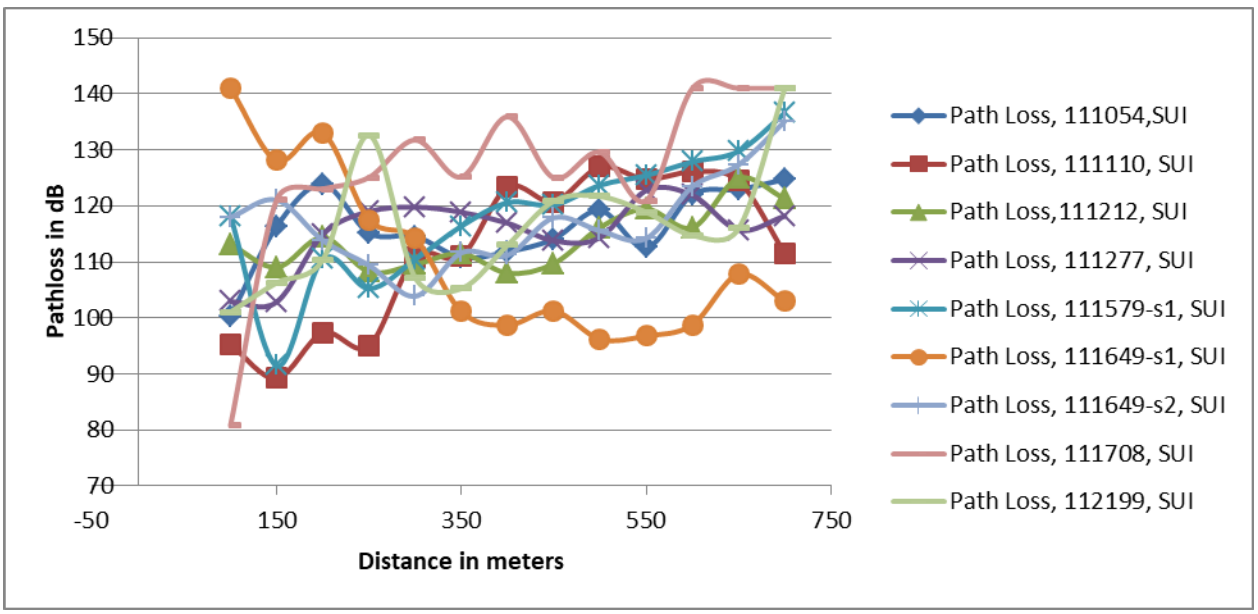


Figure 31 General Trends of collected data at selected distances for Suburban area sites (2100MHZ)

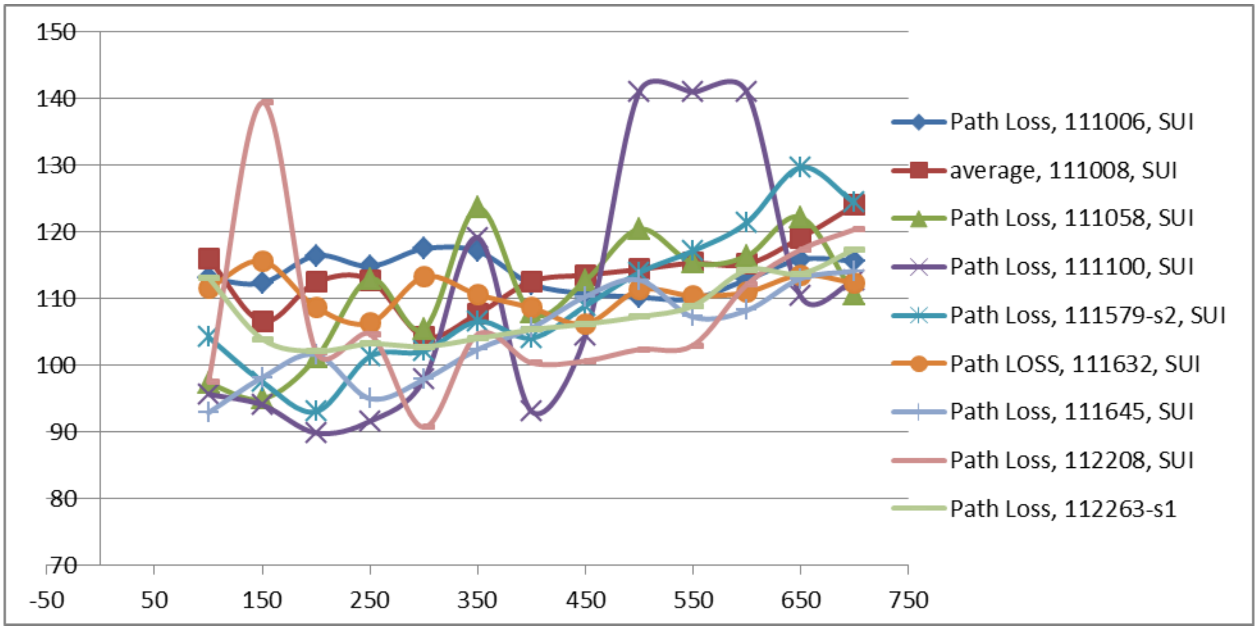


Figure 32 General Trends of collected data at selected distances for Open area sites (2100MHZ)

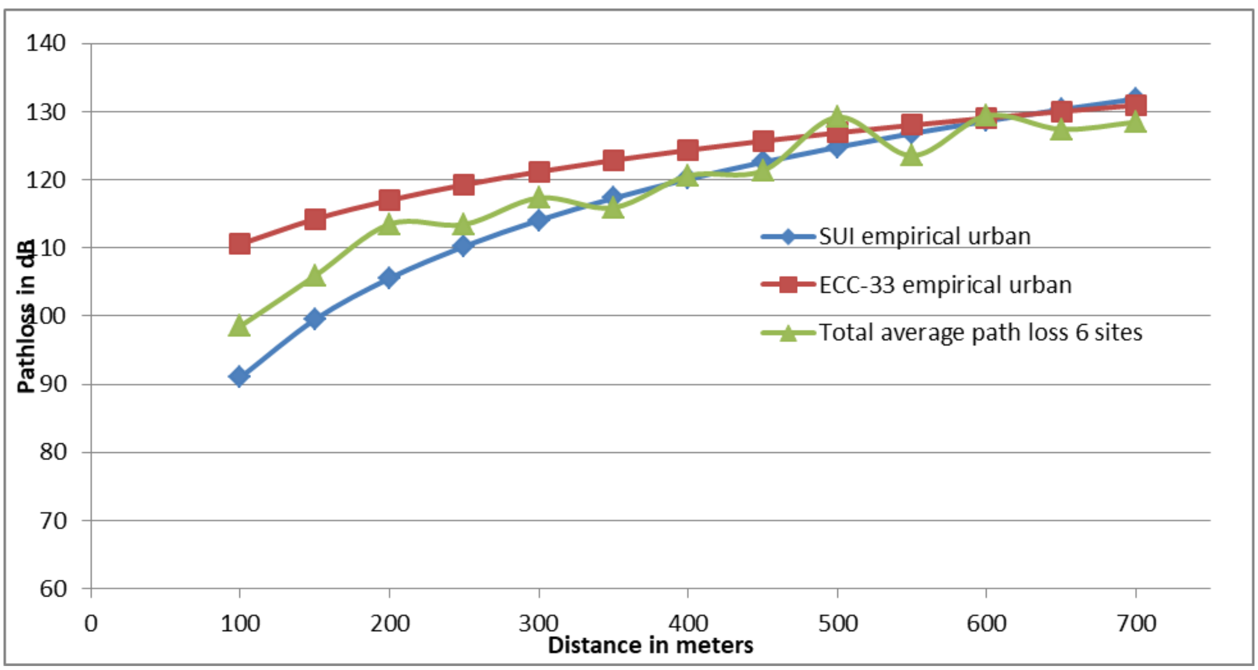


Figure 33 Path Loss for overall average value of urban area sites , ECC-33 empirical and SUI empirical models (2100MHZ)

Although both SUI and ECC-33 are performing in 50% of the urban sites, SUI could perform better than ECC-33 for the overall average path loss of urban sites. SUI has the minimum RMSE of 4.27dB as shown in the table below. So SUI is the best path loss model for urban areas.

RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST231	MAPE for SUI	MAPE for ECC
7.16	4.27	5.51	6.84	-1.68	4.27	2.12	3.92	3.48	5.82	3.12	4.15

Table 13 Performances of COST231, SUI and ECC-33 over averaged measurement of urban sites (2100MHZ)

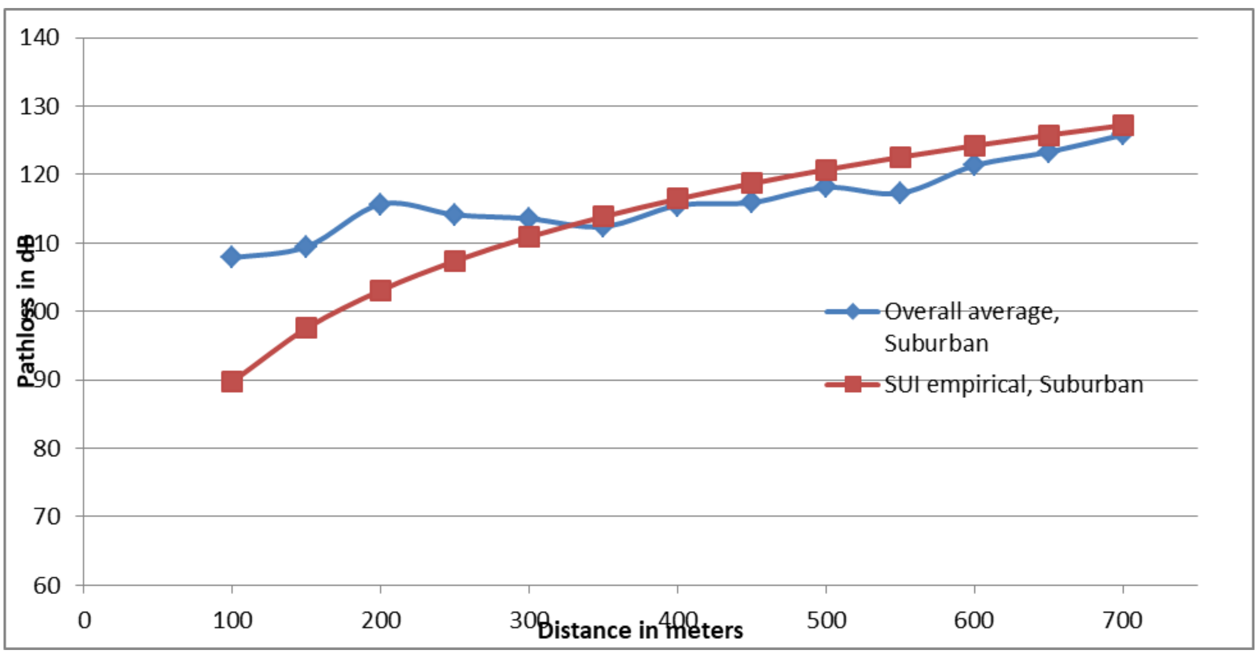


Figure 34 Path Loss for overall average value of Suburban area sites and SUI empirical model (2100MHZ)

In suburban areas also, SUI is best with RMSE value of 5.75dB as shown in the table below.

RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST 231	MAPE for SUI	MAPE for ECC
8.14	5.75	24.90	6.42	-2.47	25.39	5.09	7.13	2.82	6.26	4.88	21.87

Table 14 Performances of COST231, SUI and ECC-33 over averaged measurement of suburban sites (2100MHZ)

As previously indicated, SUI is also best for all open area sites. The figure below shows the trend of SUI and the overall average path loss for open areas.

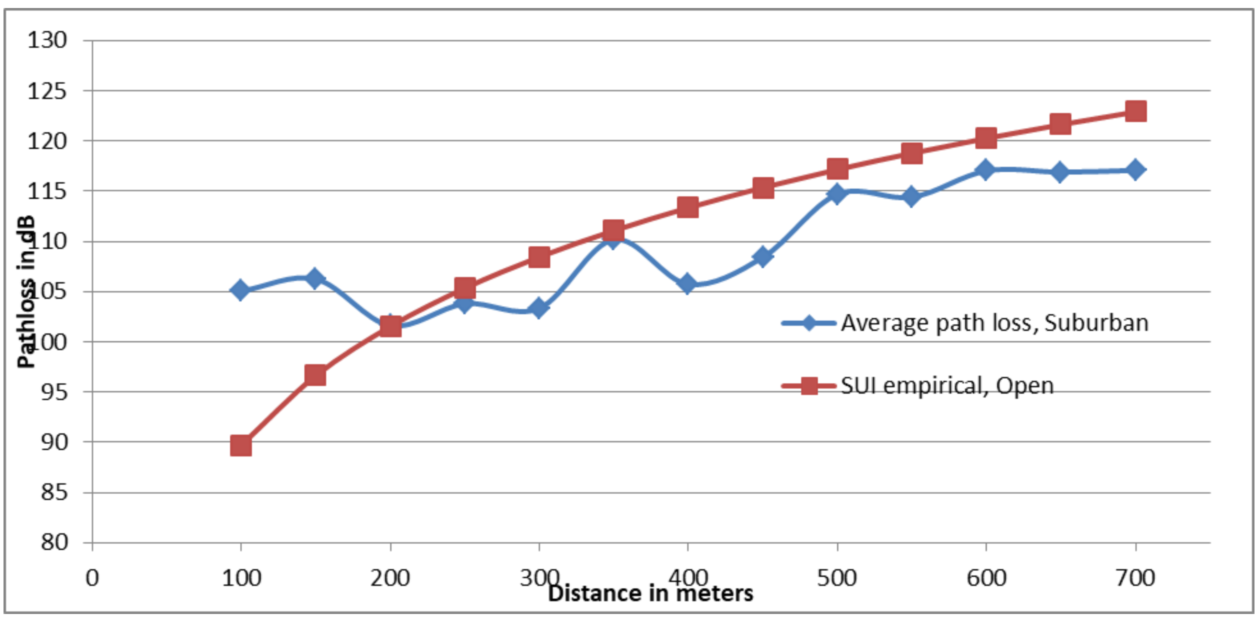


Figure 35 Path Loss for overall average value of Open area sites and SUI empirical model (2100MHZ)

And the performances of the models against the overall average is shown in the table below.

RMSE for COST231	RMSE for SUI	RMSE for ECC-33	Mean Error for COST231	Mean Error for SUI	Mean Error for ECC	Standard Deviation for COST231	Standard Deviation for SUI	Standard Deviation for ECC	MAPE for COST231	MAPE for SUI	MAPE for ECC
20.56	6.53	32.21	-19.78	1.36	32.01	5.60	6.39	3.57	18.16	4.79	29.31

Table 15 Performances of COST231, SUI and ECC-33 over averaged measurement of Open area sites (2100MHZ)

5.1.3.Model Tuning

In the previous section, it is demonstrated that COST231 is best in estimating the measured path loss data for urban and suburban areas and SUI in open areas at 1800MHZ. In 2100MHZ, ECC-33 was confirmed to be best for urban areas and COST231 for suburban areas. In this chapter we will do the tuning for all the models and calculate the RMSE values to see how the models are tunable. The tuning is done for all the three area types in the three path loss models using Linear Least Square Method (LLSM).

There are some assumptions I have to make to do the tuning. As shown in the appendixes, the tuned parameters of the path loss models depend on variables of the path loss models (MS and BS antenna heights, frequency and distance) and the data measurement. The data measurement is taken at different frequencies(f), different MS and BS antenna heights (h_m,h_b) and distances. But for the sake of simplifying the calculations, I have taken an average MS and BS antenna heights and a fixed frequency. So data measurement is considered as if it was taken at fixed antenna heights and frequency. Similarly, the path loss values from empirical models are assumed to be taken at fixed antenna heights and frequency. The effect of each variable (h_m,h_b and f) is studied in section 2.4 of Chapter two. Generally the variation of frequencies in the empirical models is shown to have no significant influence on the path loss causing only a maximum of 0.6dB variation in COST231 and the other two models with less effect for a frequency range from 1805MHZ to 1880MHZ. The same conclusion can be drawn for 2100MHZ band.

Variation of BS antenna heights from 20m to 40m causes a significant path loss variation in all the three models. There is variation in the tuning of the models by the same amount. This is also ignored for the sake of simplification. Variation in the MS antenna heights from 1m to 2m will have somehow significant variation in SUI and COST231 and negligible value for ECC-33. Hence the tuning value will get biased by the same value for SUI and COST231.

5.1.3.1. Correction Factors and Improvements after Tuning (1800MHZ)

Although COST231 was known to be best in estimating the path losses in urban area, the final selection of path loss model should be based on their tuning ability. Based on calculation done in appendix A, the optimized parameters of COST231 are shown in the table below.

The optimized value of a is	The optimized value of b is	Original Eo	Esys	Bsys	Optimized Eo	Slope correction factor, B
139.5709	36.28999	49.3	90.20673	43.7466	49.36414	0.82955

Table 16 Tuned parameters of COST231 for urban areas

The optimized COST231 equation will be

$$PL_{c231} = 49.36 + 33.9\log_{10}f - 13.9\log_{10}hb - a(h_m) + [37.27 - 5.44\log_{10}h_m]\log_{10}d$$

After tuning, the performance of COST231 for Urban area will be

RMSE for COST231	Mean Error for COST231	Standard Deviation for COST231	MAPE for COST231
3.25	0.00	8.98	2.15

Table 17 RMSE value of COST231 after tuning for urban area

And the performance of COST231 for Suburban will be

RMSE for COST231	Mean Error for COST231	Standard Deviation for COST231	MAPE for COST231
4.18	0.00	9.60	2.52

Table 18 RMSE value of COST231 for suburban

The correction factors will be

The optimized value of a is	The optimized value of b is	Original Eo	Esys	Bsys	Optimized Eo	Slope correction factor, B
139.7067	33.0574	46.3	90.20673	43.7466	49.49998	0.755656

Table 19 Tuned parameters of COST231 after tuning

SUI will have the following performance after tuning

RMSE for SUI	Mean Error for SUI	Standard Deviation for SUI	MAPE for SUI
4.91	-4.84	0.85	3.97

Table 20 RMSE value of SUI after tuning

And the correction factors will be

k1	k2
72.45931	5.590117

Table 21 Tuned parameters of SUI after tuning

5.1.3.2. Correction Factors and Improvements after Tuning (2100MHZ)

The RMSE value of the tuned SUI for urban sites will be

RMSE for SUI	Mean Error for SUI	Standard Deviation for SUI	MAPE for SUI
2.23	0.00	2.23	1.71

Table 22 RMSE value of SUI for urban sites

The tuned values of the parameters will be (based on the calculations on appendix B)

k1	k2
83.97	6.15

Table 23 Tuned parametrs of SUI for urban sites

And the tuned value of SUI for suburban will be

RMSE for SUI	Mean Error for SUI	Standard Deviation for SUI	MAPE for SUI
2.57	0.00	2.35	1.69

Table 24 RMSE value of SUI for suburban sites

The tuned values of the parameters will be (based on the calculations on appendix B)

k1	k2
106.82	1.73

Table 25 Tuned parametrs of SUI for suburban sites

The RMSE value of the tuned SUI for open area sites will be

RMSE for SUI	Mean Error for SUI	Standard Deviation for SUI	MAPE for SUI
3.38	0	3.38	2.88

Table 26 RMSE values of SUI for open area

The tuned values of the parameters will be (based on the calculations on appendix B)

k1	k2
100.1	1.75

Table 27 Tuned parametrs of SUI for suburban sites

6. Conclusion, Recommendations and Future Works

6.1. Conclusion and Recommendations

In this thesis the performance of three path loss models (COST231, SUI and ECC-33) have been investigated against field data measurement from the three possible area type (i.e. Urban, Suburban and Open areas) at 1800MHZ and 2100MHZ. More than 25 sites at distributed locations of Addis Ababa are used to collect the data. RMSE is used to measure the error between the predicted path loss values and the measured values. Based on the analysis done, the following results are obtained.

At 1800MHZ, COST231 has the biggest count in best predicting the measured path loss values that are identified to be in urban areas. It is best in 66.7% of the sites under urban area type. Still further step has been taken to select the best path loss model in this area type by evaluating the path loss models at averages of each urban site. Again COST231 was best with an RMSE value of 3.27dB. Tuning the model has improved the RMSE to 3.25dB. ECC-33 could estimate better in greater number of sites than the others in suburban areas. 50% of the sites in suburban areas could better be predicted by ECC-33. COST231 and SUI could estimate better in 25% of the sites each. In an effort to select the best model in suburban areas, all the three models were again evaluated by the average path loss of the sites. This time, COST231 was better than ECC-33 and has an RMSE value of 5.72dB. Tuning the model has improved the RMSE value to 4.18dB. SUI was best in all the open area sites with no exception. It has an RMSE value of 6.0dB for an average path loss values. Tuning has improved the RMSE value to 4.91dB.

At 2100MHZ, 25 sites are used to collect path loss data. Similar analysis was done in the three path loss models. Based on the analysis, SUI is found to be best in predicting the path loss for all the three morphology types. Although ECC-33 was equally competent for urban area sites, SUI could predict the path loss better for the overall all average measured path loss with an RMSE of 4.27dB. Tuning the model could improve the RMSE to 2.23dB. The measured path loss for suburban areas could also be better predicted by SUI with an RMSE value of 5.75dB before tuning and 2.57dB after tuning. Path loss in open areas can also be better predicted by SUI. It has an RMSE value of 6.53dB before tuning. An improvement in RMSE to 3.38dB could be achieved after tuning.

The terms urban, suburban and open areas could also be defined based on the context of the above results. Urban areas are identified by their high buildings heights (5 and above floors), high traffic flow, up & down terrain profile and narrow roads or bridge roads. Suburban areas are identified by their medium buildings heights (4 floors and below), mostly ground villa houses, medium traffic flow, wide and bending roads and sloppy & plain terrain profile. Open areas have wide and straight roads with low traffic flow, open spaces, few medium height buildings, lots of ground villa houses and mostly flat or sloppy & plain terrain profiles.

Therefore, I can conclude that COST231 is the most fitting path loss model for urban areas in Addis Ababa at 1800MHZ and other towns and cities in Ethiopia with a similar urban morphology setting and SUI is for the open areas. COST231 is still the best path loss model for suburban areas in Addis Ababa at 1800MHZ band and elsewhere with a similar suburban morphology setting SUI is the sole best path loss model in all the three morphology types at 2100MHZ band.

6.2. Future Works

Path loss estimation has vast applications in wireless communications. Unacceptable error in estimation can distort the required outputs. Cellular network planning is an imaginable without proper estimation of path losses. Unable to do that will either incur high investment cost or bring bad network quality. In this regard, selection of the best fitting path loss model is a critical step and should be an ongoing effort. Hence the following are areas that need further studies.

- Performance analysis of path loss models not considered in this thesis. Models like COST231 W-I, Egli, etc
- Seasonal effects of path loss models. This thesis considered only the rainy season.
- Field data measurement is critical for path loss model tuning and hence measurement data consistency should be focused.
- Fine tuning path loss models by considering non linearities (Small Scale Fadings)

Appendix A

Tuning COST231

Linear Least Square Method (LLSM) is used to fine tune the model.

COST231 operates in the following ranges of parameters

Frequency: 1500 – 2000MHZ

Base Station height: 30 – 200m

Mobile antenna height: 1 – 10m

The equation is given by:

$$PL_{cost231} = PL_0 - 13.82log_{10}^{h_b} - a(h_m) + \left[44.9 - 6.55log_{10}^{h_m}\right]log_{10}^{d} + C_k \text{ ------------------------- (1)}$$

Where $PL_0 = 46.3 + 33.9log_{10}^{f}$ -- (2)

C_k = area of correction factor

$$C_k = \begin{cases} \text{0dB for medium sized city and sub urban area} \\ \text{3dB for urban area} \end{cases}$$

$PL_{cost231}$ = path loss in dB

f = the carrier frequency in MHZ

h_b = base station height in m

h_m = mobile antenna height in m

$a(h_m)$ = corrective factor for mobile station

For large city (Urban),

$$a(h_m) \begin{cases} = 8.29[log_{10}^{(1.54h_m)^2}] - 1.1, \; for \; f_c <= 300MHZ \text{ ---(3)} \\ = 3.2\left[log_{10}^{(11.75h_m)}\right]^2 - 4.97, \; f_c >= 300MHZ \text{ --- (4)} \end{cases}$$

For Medium city,

$$a(h_m) = 1.1\left[log_{10}^{f_c} - 0.7\right]h_m - \left[1.56log_{10}^{f_c} - 0.8\right] \text{ -- (5)}$$

d = distance between base station and mobile station

COST231 can be optimized using least square method (LSM)

The equation can be split into three basic elements

E_o = 46.3 + C_k = initial offset parameter--- (6)

E_{sys} = 33.9$\log_{10}$f – 13.82$\log_{10}h_b$ – a(hm) = initial system design parameter-------------------------(7)

β_{sys} = [44.9 – 6.55log10h_m] = slope of the model curve---(8)

The equation can be rewritten as:

$$PL_{c231} = E_0 + E_{sys} + \beta_{sys} log_{10}^{d}$$ -- (9)

Let a = E_0 + E_{sys}

b = β sys, β - correction factor for the slope

So the equation can be written in simplified form as

$$PLc231 = a + blog_{10}^{d}$$ --- (10)

= a + bx, $x = log_{10}^{d}$

For a point i at which measurement is taken x = x_i

xi = $\log_{10} d_i$

$$PLc231i = a + bx_i$$ -- (11)

The condition of a best fit to the measured data, yi, requires that the equation below to be minimum.

$$e(a,b) = \sum_{i=1}^{n} (y_i - P(a,b))^2$$ -- (12)

Where n is the no of measured data

The minimum can be calculated by setting

$$\partial P / \partial a = 0 \; and \; \partial P / \partial b = 0$$

∂P/∂a = $\frac{\partial P}{\partial b} = \frac{\partial}{\partial b} \sum_{i=1}^{n} (y_i - P(a,b))^2$

$$= \sum_{i=1}^{n} [(y_i - P(a,b))] \left[0 - \frac{\partial P(a,b)}{\partial a} \right] = 0$$

$$= \sum_{i=1}^{n} [(y_i - P(a,b))][x_i] = 0$$

$$na + b\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i \text{ -- (13)}$$

$$\frac{\partial P}{\partial b} = \frac{\partial}{\partial b}\sum_{i=1}^{n}(y_i - P(a,b))^2$$

$$= \sum_{i=1}^{n}[(y_i - P(a,b))]\left[0 - \frac{\partial P(a,b)}{\partial b}\right] = 0$$

$$= \sum_{i=1}^{n}[(y_i - a - bx_i)][x_i] = 0$$

$$= \sum_{i=1}^{n}[(y_i - a - bx_i)][x_i] = 0$$

$$a\sum_{i=1}^{n} xi + b\sum_{i=1}^{n} xi\text{^}2 = \sum_{i=1}^{n} xi\,yi \text{ -- (14)}$$

Simultaneously solving the above two equations (35 and 36) will result in:

$$a = \frac{\sum_{i=1}^{n} xi \sum_{i=1}^{n} yi - \sum_{i=1}^{n} xi \sum_{i=1}^{n} xiyi}{n\sum_{i=1}^{n}(xi)\text{^}2 - (\sum_{i=1}^{n} xi)\text{^}2} \text{ -- (15)}$$

$$b = \frac{\sum_{i=1}^{n} xiyi - \sum_{i=1}^{n} xi \sum_{i=1}^{n} yi}{n\sum_{i=1}^{n}(xi)\text{^}2 - (\sum_{i=1}^{n} xi)\text{^}2} \text{ -- (16)}$$

Now the optimized value of Eo is

$E_0 = a - E_{sys}$ and $b = \beta \ \beta_{sys}$

$\beta = b/\ \beta_{sys} = b\ /\ 44.9 - 6.55\log10h_b$

Where a and b are obtained by substituting the measured data into the above equations.

Here the tuned Urban and Suburban COST231 model can be obtaind by plugging the optimzed variables.

Appendix B

Tuning SUI

$PL_{SUI} =$ $A' + 10\gamma\log_{10}(d/d_0) + X_f + X_h + S$ --(1)

Where $A' = 20\log_{10}(4\pi d_{ref}/\lambda)$ -- (2)

$\gamma = a - bh_b + c/h_b$ --(3)

$X_f = 6\log_{10}(f/2000)$ ---(4)

$X_h = -10.8\log_{10}(hr/2)$ for terrain of type A and B ---(5)

$= -20\log_{10}(hr/2)$ for terrain of type C --(6)

$d_{ref} = 100m$ is the reference distance

λ - wave lengh of f in m

γ – path loss exponent

h_b – base station antenna height in m

a, b,c – model parameters with specific values for each morphology types

f – operating frequency of the base station in MHZ

X_f – frequency correction factor

S – shadow fading correction factor (varies from 8.2 – 10.6)

h_r – height of the receiving station

We can see that the term A', Xf, Xh and S are all constant for a specific base station whereas the second term varies with distance.

We can rewrite the equation as:

$PL_{SUI} = k_1 + k_2B$

Where $k_1 = A' + X_f + X_h + S$

$k_2 = \gamma$

$B = 10\log_{10}(d/d_o)$

Here parameters to be tuned are γ and S as they are related to the environment. That means k_1 and k_2 are now variables.

Let PL_m be the measured path loss

The condition of a best fit to the measured data, PL_m, requires that the equation below to be minimum

$E(k_1,k_3) = \sum_{i=1}^{n}[PLmi - E(k1,k2)]^2$, *n is the no of data measured*-----------------------------(7)

The minimum E can be calculated by setting

$\partial E(k1,k2)/\partial k1 = 0$ and $\partial E/\partial k2 = 0$

$\partial E(k1,k2)/\partial k1 = \frac{\partial}{\partial k1} \sum_{i=1}^{n}[PLmi - E(k1,k2)]^2$

$= \sum_{i=0}^{n}[PLmi - PLSUIi][0 - \partial PLSUI(k1,k2)/\partial k1] = 0$

$\sum_{i=0}^{n}[PLmi - PLSUIi]\,[-1] = 0$

$nk1 + k2\sum_{i=0}^{n}Bi = \sum_{i=0}^{n}PLmi$ -- (8)

$\partial E(k1,k2)/\partial k2 = \frac{\partial}{\partial k2} \sum_{i=1}^{n}[PLmi - E(k1,k2)]^2$

$= \sum_{i=0}^{n}[PLmi - PLSUIi][0 - \partial PLSUI(k1,k2)/\partial k2]$

$\sum_{i=0}^{n}[PLmi - PLSUIi][0 - \partial PL_{SUI}(k1,k2)/\partial k2]$

$\sum_{i=0}^{n}[PLmi - PLSUIi][-Bi] = 0$

$\sum_{i=0}^{n}[PLmi - k1 - k2Bi][-B_i] = 0$

$\sum_{i=0}^{n}[PLmiBi - k1Bi - k2Bi2] = 0$

$\sum_{i=0}^{n}PLmiBi - k1\sum_{i=0}^{n}Bi - k2\sum_{i=0}^{n}Bi2 = 0$ --(9)

From eq. 46

$k_1 = \frac{1}{n}\sum_{i=0}^{n}PLmi - \frac{k2}{n}\sum_{i=0}^{n}Bi$

Inserting the above equation to 47, we get

$\sum_{i=0}^{n}PLmiBi - k_1\sum_{i=1}^{n}Bi - k2\sum_{i=1}^{n}Bi^2 = 0$

$\sum_{i=0}^{n} PLmiBi - (\frac{1}{n}\sum_{i=1}^{n} \mathrm{PLmi} - \frac{\mathrm{k2}}{\mathrm{n}}\sum_{i=1}^{n} \mathrm{Bi})\sum_{i=1}^{n} \mathrm{Bi} - \mathrm{k2}\sum_{i=1}^{n} \mathrm{Bi}\,2 = 0$

$\sum_{i=0}^{n} PLmiBi - \frac{1}{n} \sum_{i=1}^{n} \mathrm{PLmi}\sum_{i=1}^{n} \mathrm{Bi} + \frac{\mathrm{k2}}{\mathrm{n}}(\sum_{i=1}^{n} \mathrm{Bi})2 - \mathrm{k2}\sum_{i=1}^{n} \mathrm{Bi}\,2 = 0$

$k_2(\frac{1}{n}(\sum_{i=1}^{n} \mathrm{Bi})\hat{}2 - \sum_{i=1}^{n} \mathrm{Bi}\,2) = \frac{1}{n} \sum_{i=1}^{n} \mathrm{PLmi}\sum_{i=1}^{n} \mathrm{Bi} - \sum_{i=0}^{n} PLmiBi$

Combining equations 46 and 47, we get

$k_2 = \frac{n\sum_{i=0}^{n} Bi\,PLmi - \sum_{i=0}^{n} Bi\sum_{i=0}^{n} PLmi}{n\sum_{i=0}^{n}(Bi)2 - (\sum_{i=0}^{n} Bi)2}$ --- (10)

Inserting k2 into the equation of k1, we get

$k_1 = \frac{1}{n}\sum_{i=0}^{n} PLmiBi - \frac{\sum_{i=1}^{n} \mathrm{PLmiBi}\sum_{i=1}^{n} \mathrm{Bi} - \frac{1}{n}\sum_{i=0}^{n} PLmi\,(\sum_{i=0}^{n} Bi)2}{n\sum_{i=0}^{n}(Bi)2 - (\sum_{i=0}^{n} Bi)2}$

$k_1 = \frac{\sum_{i=1}^{n} \mathrm{PLmi}\sum_{i=1}^{n} \mathrm{Bi}^2 - \frac{1}{n}\sum_{i=0}^{n} PLmi\,(\sum_{i=0}^{n} Bi)\hat{}2 - \sum_{i=1}^{n} \mathrm{PLmiBi}\sum_{i=1}^{n} \mathrm{Bi} + \frac{1}{n}\sum_{i=0}^{n} PLmi\,(\sum_{i=0}^{n} Bi)2}{n\sum_{i=0}^{n}(Bi)\hat{}2 - (\sum_{i=0}^{n} Bi)\hat{}2}$

$k_1 = \frac{\sum_{i=0}^{n} Bi2\sum_{i=0}^{n} PLmi - \sum_{i=0}^{n} Bi\sum_{i=0}^{n} Bi\,PLmi}{n\sum_{i=0}^{n}(Bi)2 - (\sum_{i=0}^{n} Bi)2}$ --- (11)

Here the right values of k1 and k2 are obtained for Urban, Suburban and Open models by plugging the corresponding measured values.

Appendix C

Tuning ECC-33

$PL_{ECC} = A_{fs} + A_{bm} - G_b - G_r$

Where A_{fs} - free space attenuation

A_{bm} - basic median path loss

G_b - the BS height gain factor

G_r - the terminal (CPE) light gain factor

$A_{fs} = 92.4 + 20\log_{10}^{(d)} + 20\log_{10}^{(f)}$ ---(1)

$A_{bm} = 20.46 + 9.83\log_{10}^{(d)} + 7.894\log^{(f)}_{10} + 9.56(\log_{10}^{(f)})^2$--(2)

$Gb = \log_{10}^{(hb/200)}[13.958 + 5.8(\log^{(d)}_{10})^2$--(3)

$Gr =$ $(42.57+13.7\log^{(f)})(\log_{10}^{(hr)} - 0.585)$ for medium city --------------------------------------(4)

$0.759h_r - 1.862$ – for large city--- (5)

$PL_{ECC} = c_1 + c_2\log d + c_3(\log d)^2$,i.e. Quadratic in logarithmic scale ---------------------------------- (6)

$= c_1 + c_2x_i + c_3(x_i)^2$, where $x_i = \log d_i$

Where $c1 = 92.4 + 20\log f + 7.894\log f + 9.56(\log f)^2 - 13.958\log^{hb/200} - 0.759h_r + 1.862 + k_1$

and k_1 is the tuned offset value of A_{bm}

$C_2 = k_2 + 20$ the tuned slope value of the d-term in A_{bm}

$C_3 = -5.8\log^{hb/200}$

The tuned value should give the following error minimum

$E(c_1, c_2) = \sum_{i=1}^{n}(PLmi - PLECC)2$---(7)

$$= \sum_{i=1}^{n}(PLmi - c1 - c2\log di - (c3\log di)2)2$$

$$= \sum_{i=1}^{n}(PLmi - c1 - c2xi - c3xi2)2$$

$\partial E(c_1,c_2)/\partial c_1 = 0$ and $\partial E(c_1,c_2)/\partial c_2 = 0$

$$\frac{\partial E(c1,c2)}{\partial c1} = 0 \Rightarrow \sum_{i=1}^{n} 2\,(PLmi - c1 - c2xi - c3xi2)(0 - 1 - 0 - 0) = 0$$

$\Rightarrow \sum_{i=0}^{n} c1 + \sum_{i=0}^{n} c2 = \sum_{i=0}^{n} PLmi - c3 \sum_{i=0}^{n} xi^2$

$\Rightarrow \quad nc_1 + c_2 \sum_{i=0}^{n} x_i = \sum_{i=0}^{n} PL_{mi} - c_3 \sum_{i=0}^{n} x_i^2$ -- **(8)**

$\frac{\partial E(c1,c2)}{\partial c1} = 0 \Rightarrow \sum_{i=1}^{n} 2\left(PLmi - c1 - c2\,xi - c3\,xi^2\right)(0 - 0 - xi - 0) = 0$

$\Rightarrow \sum_{i=1}^{n} PLmixi - c1 \sum_{i=1}^{n} xi - c2 \sum_{i=1}^{n} xi2 - c3 \sum_{i=1}^{n} xi^3 = 0$

$\Rightarrow c1 \sum_{i=1}^{n} xi + c_2 \sum_{i=1}^{n} xi^2 = \sum_{i=1}^{n} PLmixi - \sum_{i=1}^{n} xi^3 - - - - **$ -------------------------- (9)

Simultaneously solving the equations 57 and 58, we get

From eq. 57 $c_1 = \frac{1}{n} \sum_{i=1}^{n} PLmi - \sum_{i=1}^{n} xi - \frac{c3}{n} \sum_{i=1}^{n} xi^2$

Inserting c1 into equation 58, we get,

$\frac{1}{n} \sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi - \frac{c2}{n} \left(\sum_{i=1}^{n} xi\right)2 - \frac{c3}{n} \sum_{i=1}^{n} xi \sum_{i=1}^{n} xi^2 + c2 \sum_{i=1}^{n} xi^2 = \sum_{i=1}^{n} PLmixi - c_3 \sum_{i=1}^{n} xi^3$

$c2 \quad \left[\sum_{i=1}^{n} xi^2 - \frac{1}{n} \left(\sum_{i=1}^{n} xi\right)2\right] = \frac{c3}{n} \sum_{i=1}^{n} xi \sum_{i=1}^{n} xi^2 + \sum_{i=1}^{n} PLmixi - c_3 \sum_{i=1}^{n} xi^3 - \frac{1}{n} \sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi$

$c_2 = \frac{\frac{c3}{n} \sum_{i=1}^{n} xi \sum_{i=1}^{n} xi^2 + \sum_{i=1}^{n} PLmixi - c3 \sum_{i=1}^{n} xi^3 - \frac{1}{n} \sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi}{\sum_{i=1}^{n} xi^2 - \frac{1}{n} \left(\sum_{i=1}^{n} xi\right)2}$ --- (10)

$= \frac{c3 \sum_{i=1}^{n} xi \sum_{i=1}^{n} xi^2 + n \sum_{i=1}^{n} PLmixi - c3n \sum_{i=1}^{n} xi^3 - \sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi}{n \sum_{i=1}^{n} xi^2 - \left(\sum_{i=1}^{n} xi\right)2}$

$c_1 = \frac{1}{n} \sum_{i=1}^{n} PLmi -$

$\frac{\frac{c3}{n} \sum_{i=1}^{n} xi \sum_{i=1}^{n} xi^2 + \sum_{i=1}^{n} PLmixi - c3 \sum_{i=1}^{n} xi^3 - \frac{1}{n} \sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi}{\sum_{i=1}^{n} xi^2 - \frac{1}{n} \left(\sum_{i=1}^{n} xi\right)\hat{}2} \sum_{i=1}^{n} xi - \frac{c3}{n} \sum_{i=1}^{n} xi^2$

=

$$\frac{\sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi^{2} - \sum_{i=1}^{n} PLmi\,(\sum_{i=1}^{n} xi)^{2} - \frac{c3}{n}(\sum_{i=1}^{n} xi)\text{^}2 - \sum_{i=1}^{n} PLmixi \sum_{i=1}^{n} xi + c3 \sum_{i=1}^{n} xi^{3} \sum_{i=1}^{n} xi - \frac{1}{n}\sum_{i=1}^{n} PLmi\,(\sum_{i=1}^{n} xi)^{2}}{n \sum_{i=1}^{n} xi^{2} - (\sum_{i=1}^{n} xi)2}$$

$$\underline{c_3(\sum_{i=1}^{n} xi^{2})2 - \frac{c3}{n}\sum_{i=1}^{n} xi^{2}\,(\sum_{i=1}^{n} xi)^{2}}$$

c_1=

$$\frac{\sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi^{2} - \frac{c3}{n}(\sum_{i=1}^{n} xi)2 - \sum_{i=1}^{n} PLmixi \sum_{i=1}^{n} xi + c3 \sum_{i=1}^{n} xi^{3} \sum_{i=1}^{n} xi - c3(\sum_{i=1}^{n} xi^{2})2 - \frac{c3}{n}\sum_{i=1}^{n} xi^{2}\,(\sum_{i=1}^{n} xi)2}{n \sum_{i=1}^{n} xi^{2} - (\sum_{i=1}^{n} xi)2}$$

=

$$\frac{n\sum_{i=1}^{n} PLmi \sum_{i=1}^{n} xi^{2} - c3(\sum_{i=1}^{n} xi)2 - n\sum_{i=1}^{n} PLmixi \sum_{i=1}^{n} xi + c3n \sum_{i=1}^{n} xi^{3} \sum_{i=1}^{n} xi - c3n(\sum_{i=1}^{n} xi^{2})2 - c3 \sum_{i=1}^{n} xi^{2}(\sum_{i=1}^{n} xi)2}{n^{2} \sum_{i=1}^{n} xi^{2} - n(\sum_{i=1}^{n} xi)\text{^}2}$$

-- (11)

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