

# Chapter 1

## Introduction

### 1.1 Introduction

Satellite communication is an important part of today's telecommunication, broadcasting, and navigation systems. The performance and reliability of satellite links are largely affected by several atmospheric parameters that attenuate the signal. Understanding and being able to accurately predict path loss due to environmental effects is required in order to design and optimize satellite communication networks. For Bangladesh, where the weather is diverse, it is preferable to model satellite path loss for enhancing the quality of satellite-based communication services.

Satellite communication path loss is caused by various factors such as free-space attenuation, atmospheric loss, rain attenuation, and cloud interference. Ground stations utilized to quantify attenuation by transmitting a dummy signal to the satellite and estimating its loss. This, however, takes resources and infrastructure on top of what is already needed. If a reliable predictive model can be established, it would eliminate the necessity of transmitting these dummy signals, thereby lessening operating expenses and boosting efficiency.

In this study, we take Bangladesh Satellite-1 and its ground base stations at Gazipur and Betbunia into account. Collecting historical attenuation data from Bangladesh Communication Satellite Company Limited (BCSCL) and relative weather data from Bangladesh Meteorological Department (BMD), a comprehensive dataset has been formed. The dataset integrates cloud, atmospheric, rain, and free-space attenuation data with various meteorological parameters. In the estimation of total accumulated attenuation, two approaches are investigated: a predictive model based on machine learning and a mathematical model. Both models' accuracy and viability are compared to ascertain their efficacy in being used as substitutes for the conventional dummy signal method. This study not only helps in the enhancement of satellite communication in Bangladesh but also offers a model that can be applied in other parts of the globe that have similar climatic conditions. By having a robust path loss model, satellite com-

munication service providers can render their networks more stable, simplify resource planning, and enhance overall service quality. The findings of this research will give valuable insights on how to mitigate atmospheric attenuation effects and offer uninterrupted satellite communication services in Bangladesh and beyond.

## 1.2 Motivation

The inspiration behind this research is the growing dependence on satellite communication for a number of important applications such as telecommunication, broadcasting, weather forecasting, and emergency services. It would be best to render these services more efficient, particularly in a developing nation such as Bangladesh, where satellite technology is emerging as a vital part of national infrastructure. One of the most essential satellite communications issues is attenuation of signals caused by atmospheric conditions. Conventional attenuation monitoring methods use dummy signals, which impose cost and complexity on satellite operations. By having a good predictive model, we can make these dummy signals obsolete, promoting operational efficiency and cost savings to satellite operators.

Besides, Bangladesh has diverse and extreme climatic conditions like high monsoons and humidity, which have a pervasive impact on signal transmission. A good path loss model will help mitigate the consequences of these challenges by providing real-time attenuation predictions, thus improved signal reliability and uninterrupted communication services.

The worldwide relevance of this study cannot be ignored since atmospheric attenuation is experienced by all satellite operators around the globe. The result of this study can be used as a reference for other regions of the world with the same meteorological climate, which will add to the general body of satellite communication and path loss modeling.

In general, this study is motivated by the demand for an inexpensive, dependable, and efficient means of enhancing satellite communication in Bangladesh and elsewhere. With the use of sophisticated machine learning techniques and mathematical modeling, we seek to establish a scientifically credible method of attenuation prediction for the general goal of increasing the level of performance of satellite-based communication systems.

## 1.3 Objective

The main goal of this research is to create an effective and precise model for predicting satellite path loss from atmospheric attenuation. Based on machine learning approaches and mathematical modeling, this research intends to establish the most appropriate method to foresee total attenuation. The main aims of this research include:

- Collecting and merging BCSCL’s historical attenuation data with BMD’s weather data to create a comprehensive dataset.
- Building a machine learning model to predict total accumulated attenuation based on meteorological data.
- Creating a mathematical model for predicting attenuation and comparing the precision with the machine learning model.
- Comparing the validity and accuracy of both models for determining their viability in replacement of conventional dummy signal-based attenuation monitoring.
- Providing data that can be utilized for optimizing satellite communication networks, reducing operational costs, and enhancing the performance of Bangladesh Satellite-1 and other similar systems worldwide.

Through these goals, this research seeks to play a role in the creation of a more efficient and resource-saving method of monitoring satellite communication signal attenuation.

## 1.4 Scope of Work

The study’s importance transcends the prediction of satellite path loss—it presents a novel and globally applicable method for optimizing the performance of satellite communications. Unlike other models needing location-dependent parameters like latitude and longitude, the mathematical model proposed in this work is not geographically limited. That is, wherever a ground station is positioned or whichever country it is in, the model is still valid.

Instead of being dependent on coordinates, the mathematical model only needs to be provided with typical weather parameters like rain rate, surface temperature, surface pressure, relative humidity, cloud base height, liquid water density in clouds, liquid water temperature in clouds, uplink frequency, polarization type, and path length. All these as inputs make the model deployable anywhere on the earth without any changes, which is a huge advantage when it comes to scalability and deployment ease.

By eliminating reliance on location-specific data, this model has the potential to be a globally viable solution for satellite communication path loss prediction. Even though improvements in accuracy are still possible, the groundwork for global usability is already there. This study, thus, not only has value in the enablement of satellite communication in Bangladesh but also makes a wider contribution by providing a model that can readily be incorporated into satellite networks worldwide.

## Chapter 2

# Background Work

### 2.1 General Path Loss Models

To understand and predict signal attenuation in wireless communication, we studied several **path loss models** that describe how the strength of a transmitted signal weakens with distance. Since wireless signals are subject to varying degrees of loss due to obstructions, reflections, and environmental conditions, multiple models help estimate actual behavior.

To compare these models, we ran **MATLAB simulations** using a 1.5 GHz (randomly selected) carrier frequency. The simulation compares three commonly used path loss models:

1. **Free-space path loss model** – perfect line-of-sight (LOS) propagation.
2. **Log-distance path loss model** – encompasses distance-dependent attenuation in different environments.
3. **Log-normal shadowing model** – encompasses random variations in signal strength due to obstacles.

All the models were run with mathematical equations for the evaluation of **signal attenuation over distance** considering different **antenna gains and path loss exponents**.

#### 2.1.1 Free-space Path Loss Model

The **free-space path loss model** assumes that a transmitted signal propagates without any obstructions. The power loss in decibels (dB) is given by:

$$PL_{free}(d) = 20 \log_{10} \left( \frac{4\pi df_c}{c} \right) - G_t - G_r \quad (2.1)$$

where:

- $d$  = Distance between transmitter and receiver (m)
- $f_c$  = Carrier frequency (Hz)
- $c$  = Speed of light ( $3 \times 10^8$  m/s)
- $G_t$  = Transmitter antenna gain (dB)
- $G_r$  = Receiver antenna gain (dB)

This model is useful for **satellite and open-area communication**, but it does not consider environmental factors like obstacles or reflections, making it **unrealistic for terrestrial communication**.

### 2.1.2 Log-distance Path Loss Model

In real-world environments, signal attenuation is influenced by the surroundings. The **log-distance path loss model** accounts for this using a path loss exponent ( $n$ ):

$$PL_{logdist}(d) = PL(d_0) + 10n \log_{10} \left( \frac{d}{d_0} \right) \quad (2.2)$$

where:

- $PL(d_0)$  = Path loss at reference distance  $d_0$
- $d_0$  = Reference distance (100 m in this study)
- $n$  = Path loss exponent (e.g., 2 for free space, 3 for urban areas, 6 for highly obstructed environments)

The path loss exponent ( $n$ ) varies based on terrain and building density. This model provides a **more practical estimation** than the free-space model but does not incorporate fading effects.

### 2.1.3 Log-normal Shadowing Model

In environments with obstacles, signal strength can fluctuate unpredictably. The **log-normal shadowing model** extends the log-distance model by adding a **Gaussian-distributed random variable** to represent signal variations due to shadowing:

$$PL_{lognorm}(d) = PL(d_0) + 10n \log_{10} \left( \frac{d}{d_0} \right) + X_\sigma \quad (2.3)$$

where:

- $X_\sigma$  = A Gaussian random variable with standard deviation  $\sigma$
- $\sigma$  = 3 dB in our simulation

This model is more realistic for urban and obstructed environments as it introduces signal variation, but it requires **statistical modeling** and does not explicitly account for multipath fading.

### 2.1.4 Implementation in MATLAB

To analyze these models, we performed MATLAB simulations using:

- Carrier frequency: 1.5 GHz
- Reference distance:  $d_0 = 100$  m
- Path loss exponents:  $n = 2, 3, 6$
- Antenna gains:  $G_t$  and  $G_r$  with varying values

The distances were taken as squared values (1, 4, 9, ..., 961) to better observe attenuation trends. Three separate plots were generated:

1. Free-space model with different antenna gains.
2. Log-distance model with varying path loss exponents.
3. Log-normal model showing shadow fading effects.

### 2.1.5 Advantages and Limitations

#### Free-space Path Loss Model:

- Advantage: Provides a simple reference for signal attenuation.
- Limitation: Does not account for obstacles or environmental interference.

#### Log-distance Path Loss Model:

- Advantage: More adaptable for different environments by adjusting  $n$ .
- Limitation: Assumes a single path loss exponent, which may not always be accurate.

#### Log-normal Shadowing Model:

- Advantage: Captures random signal variations due to obstacles.
- Limitation: Requires statistical modeling and does not include multipath fading.

### 2.1.6 Practical Considerations

While these models provide useful insights, real-world wireless communication is affected by:

- Multipath fading due to reflections and interference.
- Weather effects such as rain and atmospheric conditions.
- Dynamic obstacles like moving vehicles and buildings.
- Antenna characteristics that affect radiation patterns.

For real-world applications, more advanced models such as Hata, COST-231, ITU-R, and Rayleigh/Rician fading models are used for network design and signal prediction.

## 2.2 Okumura/Hata Model

The **Hata model** is an empirical path loss model that is used for the prediction of signal attenuation in macrocellular environments (150 MHz – 1500 MHz). It estimates path loss in urban, suburban, and open areas based on the heights of the transmitter and receiver from the ground. Our thesis is about satellite communication, where antennas are not on the ground, so this model is not applicable for our research.

### 2.2.1 Hata Path Loss Model Equation

For urban situations, the formula is as follows:

$$PL_{urban} = 69.55 + 26.16 \log_{10}(f_c) - 13.82 \log_{10}(h_{tx}) - C_{Rx} + (44.9 - 6.55 \log_{10}(h_{tx})) \log_{10}(d/1000) \quad (2.4)$$

where:

- $f_c$  = Carrier frequency (MHz)
- $h_{tx}$  = Transmitter height (m)
- $h_{rx}$  = Receiver height (m)
- $d$  = Transmitter-to-receiver distance (m)
- $C_{Rx}$  = Receiver correction factor (function of  $f_c$ )

Correction factors modify the path loss equation to account for suburban and open areas.

### 2.2.2 MATLAB Implementation

The MATLAB code:

- Computes path loss for urban, suburban, and open areas.
- Takes a carrier frequency of 1.5 GHz with  $h_{tx} = 30\text{m}$ ,  $h_{rx} = 2\text{m}$ .
- Plots results against logarithmic distance values.

### 2.2.3 Why Hata Model is Not Used in This Thesis

- Is derived from ground antenna heights, and hence cannot be used for satellite antennas.
- Is designed for use in terrestrial links, not space-based links.
- Does not take into consideration satellite path loss, where the free-space loss and atmospheric attenuation are more prominent.

Thus, alternative models like free-space path loss and satellite-specific models need to be used for our study.

## 2.3 IEEE 802.16d Model

The **IEEE 802.16d model** is an empirical path loss model used to predict signal attenuation for fixed broadband wireless systems. It classifies environments into three categories (A, B, C), based on propagation conditions, and incorporates shadowing corrections using factors from ATnT and Okumura models. Additionally, a modified version exists, which adjusts reference distance ( $d_0$ ) based on correction factors.

Since this model requires ground-based antenna heights, it is not applicable for our thesis on satellite communication, where antennas are not ground-based.

### 2.3.1 IEEE 802.16d Path Loss Model Equation

The general form of the IEEE 802.16d model is:

$$PL(d) = A + 10\gamma \log_{10} \left( \frac{d}{d_0} \right) \quad (2.5)$$

where:

- $A = 20 \log_{10} \left( \frac{4\pi d_0}{\lambda} \right) + PL_f + PL_h$  is the reference path loss at distance  $d_0$ .
- $\lambda$  = Wavelength of the signal ( $\lambda = \frac{c}{f_c}$ ).
- $\gamma$  = Path loss exponent, given by:

$$\gamma = a - bh_{tx} + \frac{c}{h_{tx}} \quad (2.6)$$

with values depending on the environment type:

- Type A:  $a = 4.6, b = 0.0075, c = 12.6$
- Type B:  $a = 4, b = 0.0065, c = 17.1$
- Type C:  $a = 3.6, b = 0.005, c = 20$

Correction Factors for Shadowing:

- ATnT Correction:  $PL_f = 6 \log_{10}(f_c/2000)$ ,  $PL_h = -10.8 \log_{10}(h_{rx}/2)$ .
- Okumura Correction:

$$PL_h = \begin{cases} -10 \log_{10}(h_{rx}/3), & h_{rx} \leq 3m \\ -20 \log_{10}(h_{rx}/3), & h_{rx} > 3m \end{cases} \quad (2.7)$$

A modified version of IEEE 802.16d adjusts the reference distance:

$$d'_0 = d_0 \times 10^{-\frac{(PL_f + PL_h)}{10\gamma}} \quad (2.8)$$

where  $d'_0$  is the adjusted reference distance.



### 2.3.2 MATLAB Implementation

The MATLAB code:

- Computes path loss for Type A environments using ATnT correction.
- Compares the original and modified IEEE 802.16d models.
- Uses carrier frequency = 2 GHz, transmitter heights = 30m, and receiver heights = {2m, 10m}.
- Plots results against logarithmic distance.

### 2.3.3 Why IEEE 802.16d Model is Not Used in This Thesis

- Requires ground-based antenna heights, which are not relevant for satellites.
- Designed for terrestrial fixed wireless systems, not space-to-ground communication.
- Does not consider satellite-specific losses, such as atmospheric attenuation or free-space propagation.

Since this model is unsuitable for satellite networks, alternative satellite-specific models are needed for our study.

## 2.4 Integration of ITU-R Propagation Models

### 2.4.1 Significance of ITU-R Propagation Models

Accurate prediction of satellite signal attenuation is crucial for developing effective and dependable telecommunication systems. Attenuation affects the strength, quality, and overall performance of signals and systems. The International Telecommunication Union Radiocommunication Sector (ITU-R) provides standardized models with accurate methodologies to estimate signal degradation caused by atmospheric effects. The three ITU-R models discussed in this section—**ITU-R P.838-3 (Rain Attenuation)**, **ITU-R P.840-9 (Cloud and Fog Attenuation)**, and **ITU-R P.676-13 (Atmospheric Gases Attenuation)**—are the core of satellite communication system planning. They ensure consistency and reliability in prediction models, resulting in the establishment of robust communication links.

Microwave and millimeter-wave satellite signals suffer severe degradation due to atmospheric absorption, scattering, and reflection. The most significant causes of signal attenuation are rain, cloud, fog, and atmospheric gases, and these must be accounted for in any satellite path loss calculation. The ITU-R models give empirical and analytical approaches to the computation of these losses and are therefore a necessity for engineers and researchers.

### 2.4.2 Explanation of Each ITU-R Model

#### ITU-R P.838-3: Model of Rain Specific Attenuation

Rain is the most powerful cause of attenuation of the signal in satellite communication, especially at frequencies above 10 GHz. **ITU-R P.838-3** provides a model to estimate rain attenuation using the power-law relation:

$$\gamma_R = kR^\alpha \quad (2.9)$$

Where:

- $\gamma_R$  is the specific attenuation (dB/km),
- $R$  is the rain rate (mm/h),
- $k$  and  $\alpha$  are frequency-dependent empirical constants.

The model encompasses polarization effects by distinguishing between horizontal and vertical polarizations. The model also provides coefficient values as a result of detailed scattering computations for precise prediction over a wide range of frequencies (1 GHz to 1000 GHz). The model plays a crucial role in **link budget analysis, fade margin design, and adaptive modulation schemes** in high-frequency satellite links.

#### ITU-R P.840-9: Attenuation in Cloud and Fog

Cloud and fog add additional attenuation, primarily at frequencies greater than 10 GHz. **ITU-R P.840-9** provides a formula for the estimation of signal loss due to cloud and fog as a function of integrated liquid water content (LWC). The model uses the following formula for attenuation:

$$\gamma_c(f, T) = K_l(f, T) \cdot \rho_l \quad (2.10)$$

Where:

- $\gamma_c$  is the specific attenuation (dB/km),
- $K_l(f, T)$  is particular cloud liquid water attenuation coefficient,
- $\rho_l$  is cloud or fog liquid water density (g/m<sup>3</sup>),
- $f$  is frequency (GHz),
- $T$  is temperature (Kelvin).

The model can be applied within a frequency band of **1 GHz to 200 GHz** and is therefore essential in the design of **Earth-space links, high-frequency terrestrial microwave systems, and next-generation satellite constellations**. Because cloud attenuation is meteorology dependent, the model further incorporates statistical distributions and global climatological information, enhancing its predictive power.

### ITU-R P.676-13: Attenuation by Atmospheric Gases

Atmospheric gases like **oxygen and water vapor** absorb electromagnetic waves, causing additional path loss. **ITU-R P.676-13** provides procedures for calculating **slant path gaseous attenuation**, considering:

- **Oxygen and water vapor absorption** due to molecular resonance effects.
- **Frequency-dependent absorption coefficients** of different atmospheric layers.
- **Correction factors for varying atmospheric conditions (pressure, temperature, and humidity).**

The model provides two primary methods:

1. **Spectral line-by-line calculations** for highly accurate attenuation estimation from individual spectral lines.
2. **Empirical fits** for quick engineering calculations in engineering applications.

The model has a very wide frequency range (**1 GHz to 1000 GHz**), and therefore it is very useful for **radio astronomy, remote sensing, and high-frequency satellite communications**. It also accounts for path elevation angles, which is crucial for **geostationary and low Earth orbit (LEO) satellite systems**.

#### 2.4.3 Reasoning Behind the Use of These Models

Use of ITU-R models in satellite path loss prediction ensures that the estimates of attenuation are:

1. **Scientifically Validated:** The models have been developed through extensive experimental and theoretical work, hence reliable.
2. **Frequency-Dependent:** Each model is specific to specific frequency bands, so they can be used across various bands utilized in satellite communications.
3. **Geographically Adaptive:** Global meteorological datasets are used in the models, which allows location-based predictions.
4. **Global Standardized Use:** ITU-R recommendations are commonly adopted, allowing interoperability among various communication systems and compliance with the regulations.

All the models are used for specific purposes:

- **ITU-R P.838-3** is critical for **rain attenuation predictions**, which have a great influence on satellite links in tropical and high-rainfall environments.
- **ITU-R P.840-9** deals with **cloud and fog attenuation**, which is important for systems that function in humid environments and high-frequency bands.
- **ITU-R P.676-13** also incorporates **gaseous attenuation**, important to apply to precise signal strength calculations, particularly in long-haul satellite transmissions.

Through their application, these models enable satellite communication systems to more effectively take advantage of **power budgets, antenna designs, frequency selection, and adaptive coding schemes**, leading eventually to a better link reliability and overall performance.