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Original Article

Performance Analysis of Lee, Dual Slope & ITU-RP.833 Path Loss Models for LoRa-WSN in Dense Forest Monitoring

Sagar R. Pradhan[1], Gajendra M. Asutkar[2], Kiran Asutkar[3]

[1,2]*Department of Electronics and Communication Engineering, Priyadarshini College of Engineering, Nagpur, India.*
[3]*Department of Civil Engineering, Government College of Engineering, Nagpur, India.*

[1]*Corresponding Author : sp8728@outlook.com*

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Abstract *- Wireless sensor Networks operating in dense forest environments, LoRa LPWAN systems, face significant challenges due to dense foliage and obstructions. Accurate path loss models are crucial for designing and optimizing such systems. This research article presents a comparative analysis of three path loss models, namely Lee, Dual Slope, and ITU-R P.833, for a LoRa LPWAN system deployed in dense forest monitoring applications. The performance of these models is evaluated based on their ability to predict signal strength in challenging forest environments. Field measurements are conducted in a dense forest area, capturing various characteristics using a simulation approach such as SINR, Attenuation, path loss exponent and foliage densities. The obtained simulated data is used to validate and compare the path loss models against the measured results. The analysis considers distance, antenna heights, and environmental conditions specific to dense forests. The results provide insights into the suitability and accuracy of the path loss models, aiding in designing and optimising LoRa LPWAN systems for effective monitoring in dense forest environments. This study contributes to understanding path loss modelling in challenging forest scenarios and enables informed decision-making in deploying wireless communication systems for forest monitoring applications. A thorough comparison of three path loss models for LoRa LPWAN systems in dense forest environments has been presented.*

Keywords *- Dense forest monitoring, Dual slope model, ITU-R P.833 model, Lee model, LoRa-LPWAN, Path loss models, Signal attenuation, Spreading factor.*

1. Introduction

Dense forest environments present unique challenges for wireless communication systems, particularly in the context of monitoring applications. Effective monitoring of dense forests requires reliable and robust wireless connectivity to transmit critical data and enable real-time analysis [1, 2]. Low Power Wide Area Network (LPWAN) techniques, such as LoRa (Long Range), have emerged as promising solutions due to their long-range capabilities, low power consumption, and suitability for Internet of Things (IoT) applications[3, 8, 9]. However, deploying a LoRa LPWAN system in dense forest areas poses significant challenges due to dense foliage, which causes signal attenuation and degradation due to path loss. Accurate path loss prediction is essential for designing, deploying, and optimising wireless communication systems in dense forest monitoring scenarios[16].

Path loss models are crucial in estimating the signal strength at different distances and locations within the forest. Several path loss models have been proposed in the literature, each offering varying levels of accuracy and applicability to different environments. In this research article, we compare the performance of three path loss models, namely Lee, Dual Slope, and ITU-R P.833, for a LoRa LPWAN system in dense forest monitoring. The Lee model is widely used in wireless.

Communication applications consider terrain features, but their accuracy in dense forests is uncertain. The Dual Slope model incorporates line-of-sight and non-line-of-sight components, offering improved accuracy. The ITU-R P.833 model, developed by the International Telecommunication Union, is designed explicitly for point-to-area predictions and accounts for environmental factors [10-14].

This study aims to evaluate and compare the suitability and accuracy of these path loss models. The measured data is then used to validate and compare the predictions of the path loss models. The findings of this research will provide valuable insights into the performance of path loss models for LoRa LPWAN systems in dense forest environments. These insights will aid in designing, optimising, and deploying wireless communication systems for effective monitoring and data transmission in dense forest applications. By enhancing our understanding of path loss modelling in challenging forest scenarios, this study contributes to advancing wireless communication technology in the context of forest monitoring [16].

The rest of the paper is organized as follows. Section 2 provides an overview of the related work in path loss modelling. Section 3 describes the methodology used for field measurements and data collection. Section 4 presents the design of the simulation experiment and mathematical modelling used to investigate the parameter of the path loss model. Section 5 discusses the results and implications of the findings and their significance for dense forest monitoring applications. Finally, Section 6 concludes the paper and outlines future research directions.

2. Related Work

The performance analysis of the Path Loss model using LoRa LPWAN demonstrates its effectiveness in providing long-range communication with low power consumption [1-6]. Using SX1278 LoRa in forest monitoring showcases its remarkable performance and suitability for this specific application. The technology's long-range capabilities enable seamless communication over vast and obstructed forest areas, making it an ideal choice for monitoring remote and hard-to-reach locations.

The low power consumption of the SX1278 LoRa module ensures prolonged battery life for monitoring devices, minimizing the need for frequent maintenance or battery replacements in challenging environments[18]. Its ability to penetrate foliage and obstacles allows for reliable data transmission, enabling real-time or periodic updates on environmental parameters such as temperature, humidity, and air quality.

However, potential limitations like interference from other wireless devices or signal attenuation in dense vegetation should be considered during implementation[7]. Overall, SX1278 LoRa demonstrates great promise in enhancing forest monitoring efforts by providing an efficient, cost-effective, and robust communication solution in such critical ecosystems [10, 12, 19].

The study thoroughly examines the accuracy and reliability of the path loss model, which is essential for estimating signal attenuation and coverage prediction in LoRa networks. The author reviewed the basic models in this research work: Lee, Dual Slope and ITU-RP. The detailed description mentions;

Lee Model: The Lee path loss model is widely used in various wireless communication systems due to its simplicity and effectiveness. Lee’s model considers the effect of path loss due to both free space loss and shadowing caused by obstacles in the environment. However, the Lee model may not accurately capture the path loss characteristics in dense forest monitoring scenarios, where the foliage and trees create additional obstructions. Several studies have reported that the Lee model tends to underestimate path loss in dense forest environments [10, 11, 15].

Dual Slope Model: The Dual Slope path loss model addresses the challenges posed by non-line-of-sight (NLOS) environments, making it suitable for dense forest monitoring applications. This model incorporates two path loss slopes, one for the line-of-sight (LOS) component and another for the NLOS component. By accounting for the scattering and diffraction effects caused by trees and foliage, the Dual Slope model has demonstrated improved accuracy in predicting path loss in dense forest scenarios [12-16].

ITU-R P.833 Model: The ITU-R P.833 model is a widely accepted path loss model for terrestrial fixed services and has been extensively used for coverage analysis in various environments. However, its applicability to dense forest monitoring with LoRa LPWAN systems is relatively limited. The ITU-R P.833 model does not explicitly consider the effects of tree and foliage attenuation, which are crucial in accurately characterizing path loss in dense forest environments. Hence, its accuracy may be compromised when deployed in such scenarios [15-17].

Comparative Analysis: Several comparative studies have been conducted to evaluate the performance of these path loss models in dense forest monitoring for LoRa LPWAN systems.

Overall, the Dual Slope model has shown superior accuracy to the Lee and ITU-R P.833 models in capturing the complex propagation characteristics in dense forest environments. The Dual Slope model accounts for the significant effects of scattering and diffraction caused by trees and foliage, leading to more reliable path loss predictions [10-17].

3. Materials and Methods

3.1. Study Area Selection

The measured region's forest geographical and meteorological data, as shown in Figure 1 (Near Village: Hingna, district: Nagpur, State: Maharashtra, Country India), is collected using Low Power Wireless Area Network (LPWAN). The temperature, relative humidity and acoustic sensor value to detect unethical activity are measured for forest monitoring [17].

3.2. WSN Deployment

3.2.1. Architecture

By carefully considering sensor selection, placement, network architecture, and data collection procedures, the wireless sensor network deployment ensures the availability of accurate and reliable data transmission [17]. Figure 2 shows the basic block diagram of single-node architecture.

3.2.2. Network Configuration

The forest monitoring system incorporates the controller ESP8266 development board, DHT, Acoustic sensor and LoRa SX1278 module for long-range communication. The Node-MCU board help coordinate the data acquisition and transmission processes. The DHT sensor provides valuable environmental data. The sensor nodes (N1, N2, N3 and N4) are deployed at a distance of 400m, 800m, 750m and 300m, respectively. The data packets are received by a central gateway, where further processing and analysis take place using the Thingspeak IoT Platform [17].

Table 1 provides the Sensor node Numerical value for mathematical modelling and theoretical calculation. Implementation of Lee, Dual Slope, and ITU-R P.833 path loss models simulated using MATLAB 2021b programming.

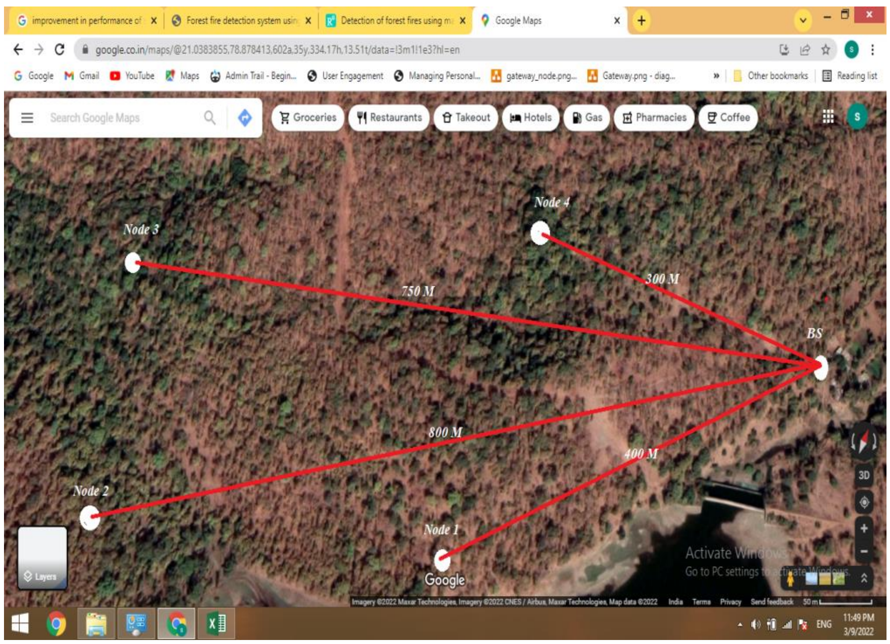

Fig. 1 Meteorological location of the study conducted

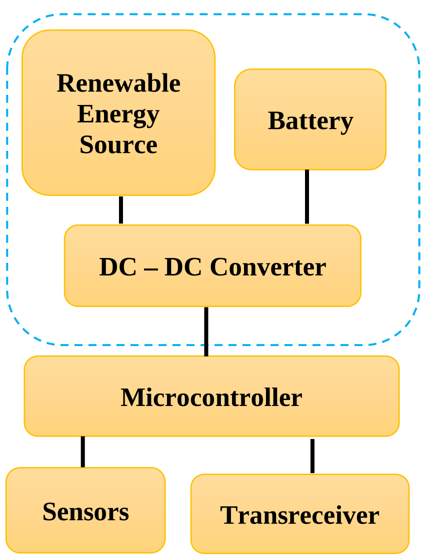

Fig. 2 Single node architecture

Table 1. Sensor node specification (experimental value)

Sr. No	Parameter		Values	Reference
LoRa SX1278				
01	Operating Frequency (f)		433 MHz	[21]
02	Antenna Transmitter Gain (G_{TX})[19, 20]		20 dBm	
03	Antenna Receiver Gain (G_{RX})[19, 20]		-148 dBm	
04	Average Antenna Height (both transmitter and Receiver) (h)		3 m	Experimental Setup
05	Distance (d)	d1	400 m	Refer Figure 1
		d2	800 m	
		d3	750 m	
		d4	300 m	
06	Data Rate		0.3 Kbps to 50 Kbps	[21]
07	Bandwidth		125 KHz	
Microcontroller (Node MCU)				
08	Energy Consumption	Active Mode	0.5 J	As per mathematical calculations from the datasheet
		Idle Mode	0.5 J	
		Sleep Mode	0.3 J	

4. Mathematical Modelling

To estimate the performance of Low Power Wide Area Networks (LPWAN) in dense forest monitoring, we can consider a mathematical model that considers various factors such as signal propagation, path loss, interference, and data rate. The path loss model breaks down into different components:

4.1. Signal Propagation Model

4.1.1. Free Space Path Loss (FSPL) Model

This model estimates the loss of signal strength as the signal propagates through space without any obstacles.

The FSPL is given by the equation

$$FSPL(d) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}(c) - G_{TX} - G_{RX} \quad (1)$$

Where,
d: distance between the transmitter and Receiver
f: Frequency of the signal
c: speed of light or Signal Propagation
G_{TX} : transmitter gain
G_{RX} : receiver gain

4.1.2. Path Loss Model in Forest Environment

Forest path loss models consider vegetation's effects on signal propagation. These models incorporate tree density, height, and foliage density parameters. Examples of forest path loss models include the Lee Model, the Dual-Slope Model, or the ITU-R P.833 model. The specific model depends on the characteristics of the dense forest being monitored[16].

4.1.3. Interference Model

LPWAN networks typically operate in unlicensed frequency bands, which can be susceptible to interference from other devices or networks. The interference can be modelled using metrics such as Signal-to-Interference-Noise Ratio (SINR) or Signal-to-Noise Ratio (SNR)[18], frequency utilization, spreading factor, path loss exponent and attenuation for LoRa WSN in dense forest monitoring[9, 10].

To evaluate the performance through a simulation approach, we combine these models to estimate coverage range, received signal strength, packet error rate, or network capacity. The equations will depend on the chosen models and parameters for LPWAN technology and forest environment.

Forest Path Loss Calculation

The path loss model for estimating signal attenuation in dense forest conditions is shown in Figure 3. Basically, it considers the effects of tree height and tree density during signal propagation.

The trees are assumed to be randomly distributed, and the ground reflection is neglected (equal to zero). The generalized path loss Model can be modelled as:

$$P_L = 20 \times \log_{10}(d) + 10 \times \log_{10}(f) + A - B \quad (2)$$

Where,
P_L : path loss in decibels (dB),
d: distance between the transmitter and Receiver in meters,
f: Frequency of signal in hertz (Hz),
A: attenuation due to tree density in dB,
B: attenuation due to tree height in dB.

The attenuation due to tree density (A) is calculated as

$$A = \alpha \times \rho \times (1 - e^{(-\beta \times \rho)}) \quad (3)$$

Where,
α: path loss per unit tree density dB/m^2
β: the slope of the path loss curve in dB/m^2
ρ: tree density in number of trees per square.

The attenuation due to tree height (B) is calculated as follows:

$$B = \gamma \times h \quad (4)$$

Where,
γ: path loss per unit tree height in dB/m,
h: average tree height in meters.

The values of α, β and γ are determined through experimental observation measurements for the dense forest condition. Hence equation 2 is modeled as follows;

$$P_L = 20\log_{10}(d) + 10\log_{10}(f) + \{\alpha \times \rho \times (1 - e^{(-\beta \times \rho)})\} - \{\gamma \times h\} \quad (5)$$

Attenuation Calculation

To design a mathematical model for the attenuation in the ITU-R P.833, Lee, and Dual-Slope models, we represent the path loss (attenuation) as a distance function. Here is a mathematical representation for each model:

Lee Model:The Lee model considers the path loss exponent and additional factors. It can be represented mathematically as;

$$\text{Attenuation}_{\text{Lee}} = 20\log_{10}(d) + 20\log_{10}(f) \; 27.55 + (n_{\text{Lee}} 20\log_{10}(d)) + 20\log_{10}(10) \quad (6)$$

Where,
$Attenuation_{Lee}$: attenuation in dB.
d: distance in meters.
f : Frequency in Hz.
n_{Lee} : path loss exponent for the Lee model

Dual Slope Model: The Dual-Slope model considers two different path loss exponents and a distance threshold for switching between them. It can be represented mathematically as:

$$\text{Attenuation}_{\text{Dual Slope}} = \begin{cases} P_{L0} + n_1 10\log_{10}\left(\frac{d}{d_0}\right) & \text{if } d \le d_1 \\ P_{L0} + n_1 10\log_{10}\left(\frac{d_1}{d_0}\right) + n_2 10\log_{10}\left(\frac{d}{d_1}\right) & \text{if } d > d_1 \end{cases} \quad (7)$$

Where,
$\text{Attenuation}_{\text{DualSlope}}$: attenuation in dB.
d : distance in meters.
P_{L0} : reference path loss at the reference distance d_0.
n_1 : path loss exponent for the first segment.
n_2 : path loss exponent for the second segment.
d_0 : reference distance.
d_1 : distance threshold for switching to the second segment.

ITU-R P.833 Model: The ITU-R P.833 model calculates the path loss based on the distance and Frequency. It can be represented mathematically as:

$$\text{Attenuation}_{\text{ITU-R}} = -22\log_{10}(d) - 20\log_{10}(f) + 20\log_{10}(10) \quad (8)$$

By considering the mathematical modelling and the experimental values depicted in Table 1 the results were plotted for frequency utilization, spreading factor, path loss exponent and attenuation for LoRa WSN in dense forest monitoring.

5. Results and Discussion

The bandwidth utilization of the LoRa LPWAN system against the spreading factor has been observed and shown in Table 2. The variation of Bandwidth utilization against the spreading factor has been plotted in Figure 5.

It indicates that as the distance of LoRa increases, spreading factor also increases and results in Bandwidth suppression. With the help of mathematical modelling and simulation using MatLab 2021b version, the path loss and attenuation parameter has been calculated over the distance of 0m to 1000m in a dense forest environment for Lee, Dual slope and ITU-R P.833.

It is observed that ITU-R P.833 model provides a maximum power loss of about (250-300)dB, and the Dual slope model provides a minimum power loss upto (50-100) dB compared to the Lee model.

The attenuation is a maximum of about 200dB for the ITU-R P.833 model and a minimum of about negative (300 - 400) dB for the Lee model.

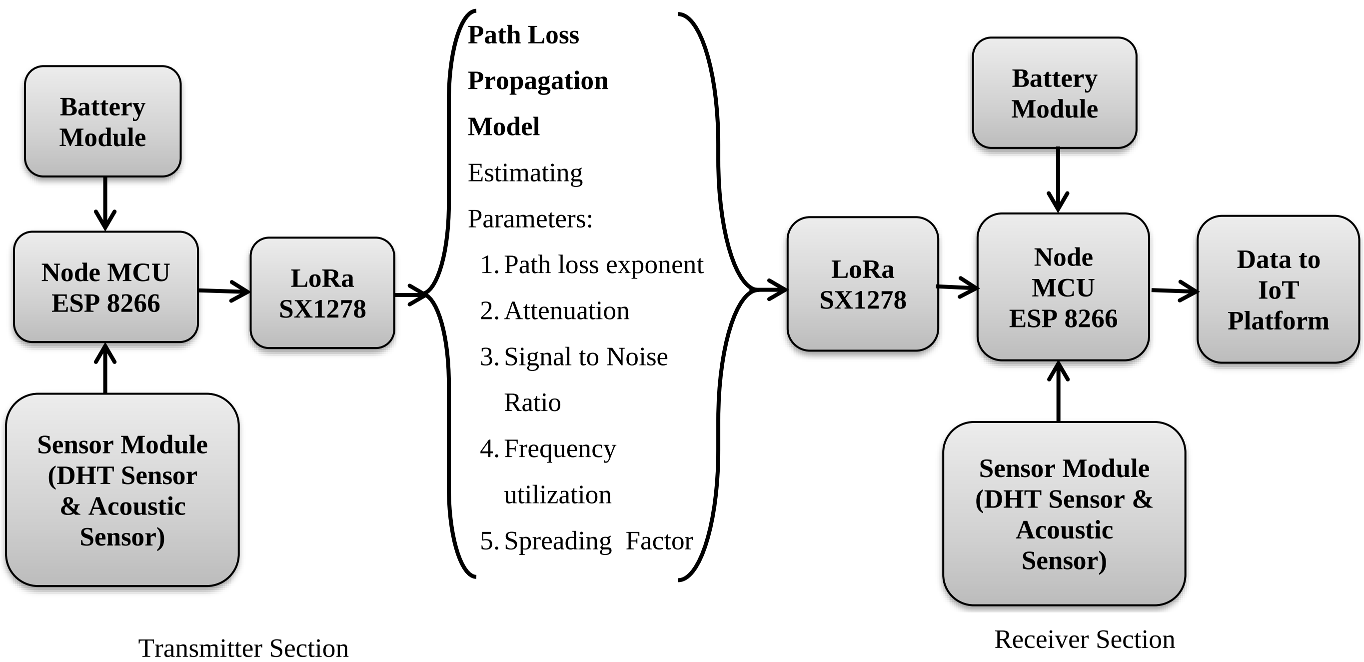

Fig. 3 Path loss propagation model for LoRa LPWAN (WSN) in dense forest monitoring

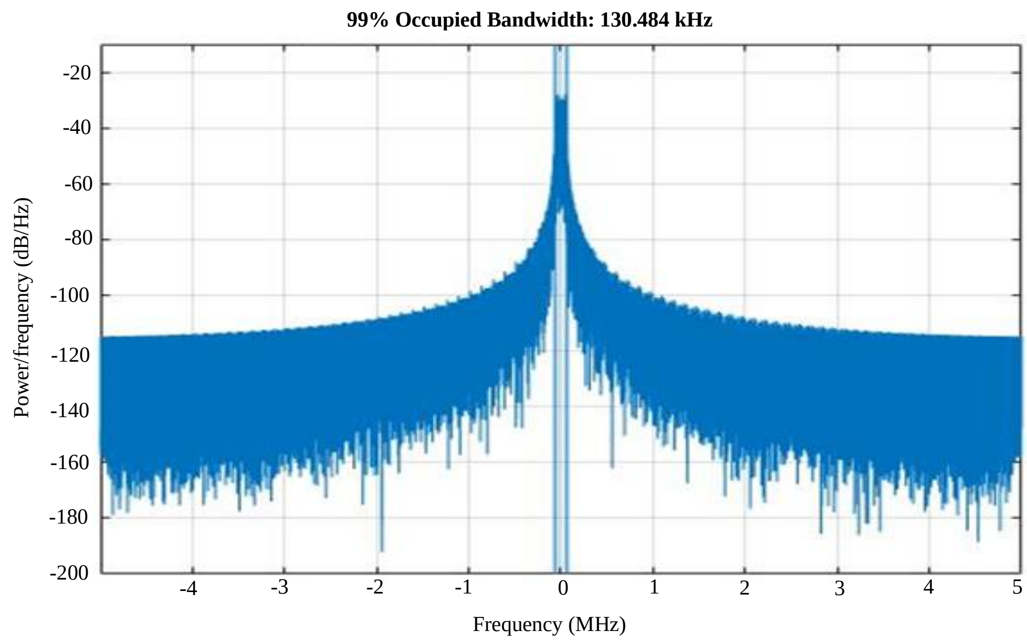

Fig. 4 Bandwidth utilization of LoRa LPWAN for spreading factor (sf)=07

Table 2. Spreading factor vs Bandwidth utilization

Sr. No	Spreading Factor	Bandwidth Utilization (KHz)
01	07	130.484
02	08	126.535
03	09	124.721
04	10	123.705
05	11	123.350
06	12	2.5

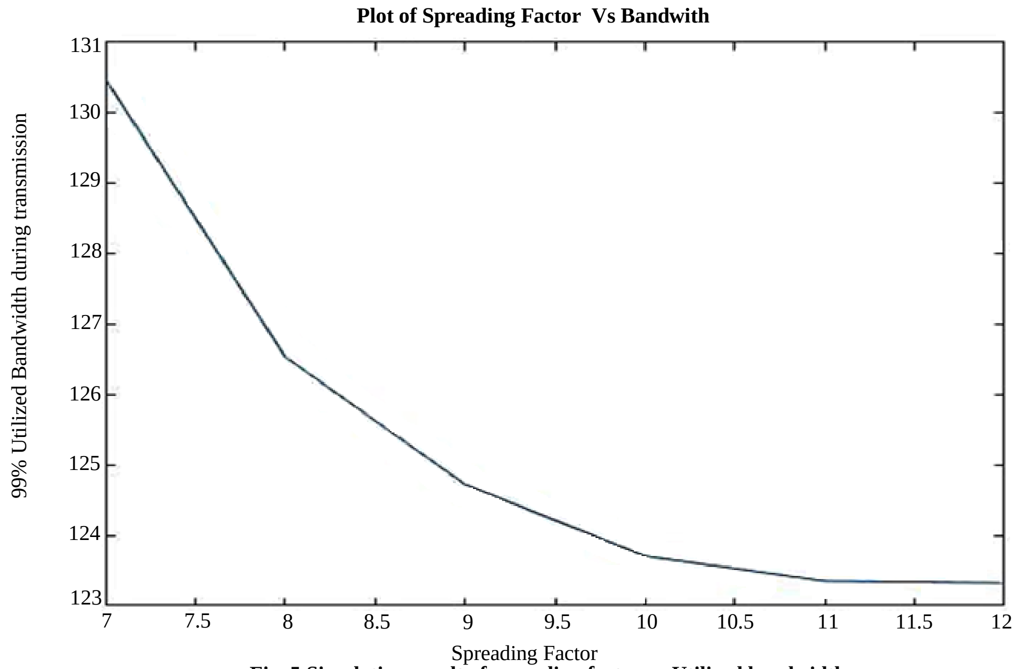

Fig. 5 Simulation result of spreading factor vs Utilized bandwidth

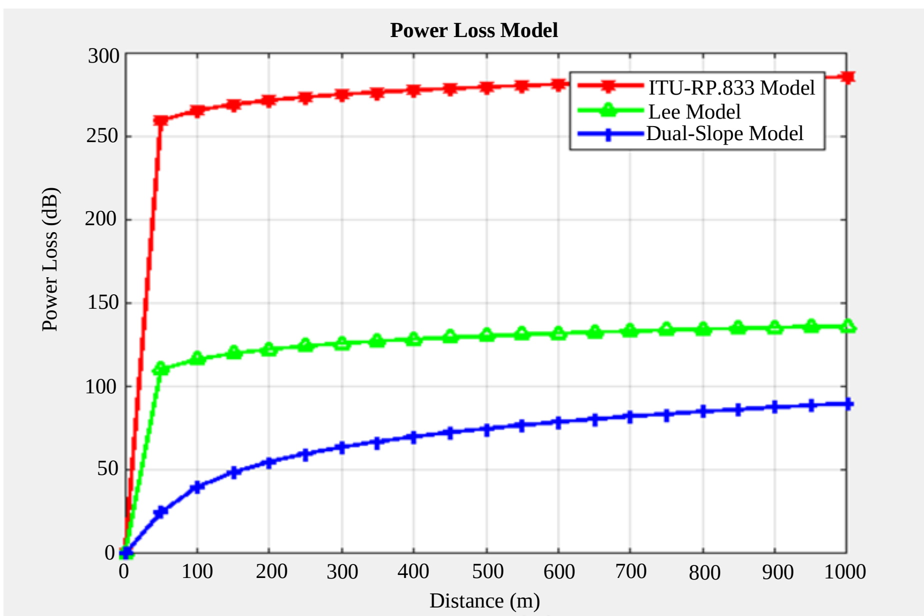

Fig. 6 Plot for power loss in case of lee, dual slope and ITU-R P.833 models

The comparative analysis of our proposed system with other technology is shown in Table 3. The study examined parameters such as standard, frequency band, modulation type, channel bandwidth, power consumption, data rate, communication range, cost, and network topologies. ZigBee, adhering to IEEE 802.15.4 standard, operates in the frequency bands of 868/915 and 2.4 GHz, with a channel bandwidth of 2 MHz and a communication range of 100 meters. It showcases low power consumption and low 20, 40, and 250 kbps data rates. Bluetooth Low Energy, following IEEE 802.15.1, operates solely in the 2.4 GHz frequency band with a narrower bandwidth of 1 MHz, limiting its communication range to 10 meters. It boasts ultra-low power consumption and a data rate of 1 Mbps. WiFi, based on IEEE 802.11a, b, g, n, utilizes the 2.4 GHz frequency band with a channel bandwidth of 22 MHz, providing a communication range of 100 meters and data rates ranging from 11 to 150 Mbps. However, it exhibits higher power consumption compared to the other technologies. Our proposed system utilizing LoRa technology, adhering to IEEE 802.15.4g, operates at 433 MHz with a channel bandwidth of 125-130 KHz, enabling a communication range of 500 to 1000 meters with propagation loss and can be evaluated with the help of Lee, Dual Slope and ITU-R P.833 Models. It stands out with shallow power consumption and a data rate of 50 kbps. Hence, the LoRa-based system is cost-effective and supports star-of-stars network topologies, offering versatile deployment options.

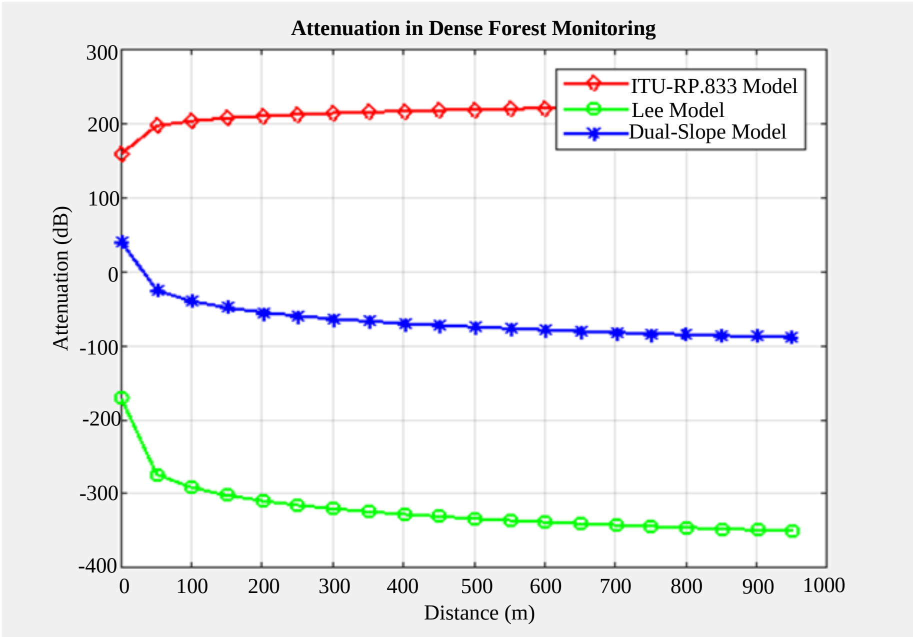

Fig. 7 Plot for attenuation in case of lee, dual slope and ITU-R P.833 models

Table 3. Comparative analysis of proposed path loss model with other technology

Sr. No	**Parameters**	**ZigBee**	**BLE**	**Our Proposed System (LoRa)**
Reference		[1][4]	[5][6][7]	
1	Wireless Standard	IEEE 802.15.4	IEEE 802.15.1	IEEE 802.15.4g
2	Frequency Band	868/915 MHz and 2.4 GHz	2.4 GHz	433 MHz
3	Modulation type	BPSK/OQPSK	GMSK	GFSK
4	Channel Bandwidth	2 MHz	1 MHz	125-130 KHz
5	Power Consumption	Low	Ultra-low	Very Low
6	Data Rate	20, 40, and 250 kbps	1 Mbps	50 kbps
7	Communication Range	100 m	10 m	500m-1000m with Propagation loss
8	Cost	Low	Low	Low Cost
9	Network Topologies	P2P, tree, star, mesh	Star-bus	Star-of-stars

6. Conclusion

This research article thoroughly compares three path loss models for LoRa LPWAN systems in dense forest environments. The study demonstrated the importance of accurate path loss modelling in designing effective wireless communication systems for forest monitoring applications. We evaluated the Lee, Dual Slope, and ITU-R P.833 models' performance in predicting signal strength amidst dense foliage and obstructions through extensive field measurements and rigorous analysis. The results revealed that while all three models showed varying degrees of accuracy, the ITU-R P.833 model exhibited the best overall performance in dense forest scenarios. Its ability to account for characteristics and foliage densities provided more reliable signal strength predictions, ensuring better system design and optimization. A result fosters advancements in forest monitoring applications and facilitates the implementation of efficient and resilient LoRa LPWAN systems in dense forest regions, further promoting environmental monitoring and conservation efforts.

Acknowledgments

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