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Measurement and Modeling of RF Propagation in Forested Terrains for Emergency Communication

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ABSTRACT

Emergency teams need dependable RF communication in the woods and in remote areas where there is no regular infrastructure. But signal travels in a forest area are difficult due to signal bouncing, attenuation by leaves, and the effects of changing ground heights. A measurement experiment and the creation of models were carried out to better understand and improve communication in emergencies within forests. The measurements were made using portable RF equipment in three frequencies: 150 MHz (VHF), 450 MHz (UHF), and 1.2 GHz (L-band). They were taken under a wide range of forest types, some with tall trees, others with short ones, and in different wetness conditions. By looking at the sample data, we worked to characterize path loss, direct signal delay spread, and shadowing. Researchers checked how well the MED, ITU-R, and Weissberger models matched up with real-world data. A new model is introduced, which uses both empirical and statistical methods to make better predictions of RF path loss in emergencies close to forests. These findings back up the call for improving wireless networks and help develop useful protocols for emergency communication in vegetation.

1. INTRODUCTION

In the wake of natural disasters such as wildfires, landslides, or storms, reliable cell phones and other wireless devices are really important for helping rescuers work together and sharing important updates. Forested regions, where many of these emergencies happen, make it very hard for RF communication systems to do their job. The thick plants, uneven land, and high amount of moisture in these parts of the world can make it really hard for phone signals to travel well and can make the signals weak and less reliable. Traditional communication systems often are hard to reach or broken in these kinds of places, which shows how important it is to have strong wireless communications that work well there.

Understanding how signals travel through forests is important so that we can make emergency communication systems that cover enough area and can be trusted to keep working. Unlike quiet streets or suburb areas, forests can cause more issues for cell phone signals, like leaves soaking up the signal, trees scattering it, the ground bouncing it back, and changes depending on the weather. While there are a few types of propagation models—like the simple known-as-empirical ones and a bit more complicated ones that are sort of half-predictable—they often have a hard time getting the right idea of how the signal will act when it hits different and moving types of vegetation.

This research tries to close this gap by making careful measurements in forested areas with all kinds of tree cover and then checking those results against the current models to see if they can be improved. Furthermore, the study suggests a new way of looking at how radio waves travel that mixes things people have seen in real life with basic statistics, to help more accurately predict how well signals work in forested areas. The outcomes of this work are expected to help improve emergency communication systems, especially in places where natural disasters and lots of plants are common.

2. LITERATURE REVIEW

Radio frequency (RF) propagation in forested places has been important to research for several years, because it is needed in military, monitoring, and disaster relief work. Because vegetation causes signal loss, fading problems, and shadowing, wireless communication is impaired. It is therefore very important to correctly model such areas for emergency work.

2.1 Classical Empirical Models

Early work in modeling signal loss in vegetation focused on using real-world data from forests and wooded areas to come up with simple, measured-based models. Weissberger's Vegetation Model, which is used in a lot of cases, figures out how much radio waves get lost by plants depending on how thick the grass or trees are and the radio frequency being used. It gives a good guess for medium amounts of vegetation, but the model can often overestimate how much is removed in thin forests and underestimate it in really thick, rainy forests.

The ITU-R P.833 model, made by the International Telecommunication Union, gives us simple attenuation curves and ways to predict fading based on real measurements made in the field. It looks at how much distance foliage causes, and how often your antenna will need to switch from one frequency to another, with frequencies ranging from very high (VHF) to super high (SHF). However, its accuracy gets worse when looking at places with different levels of land and trees because the area around the imaging system can cast a lot of shadows and make the height of objects look weird.

2.2 Site-Specific and Semi-Empirical Models

To make the models more accurate in different types of vegetation, many researchers suggested using a mix of different kinds of models or using simplified versions of the more complicated models. The Modified Exponential Decay (MED) model has exponential decrease functions that show how everything like leaves, twigs, and even the ground underneath plays a part in how the sound fades away. This model is often used in different simulation studies because it can work well for places where the trees and plants aren't spread out evenly.

Tamir's two-layer model sees the ground and everything above it made up of different layers stacked on top of each other, where the trees are treated like material that helps scatter and reflect radio waves. While the theory behind this model seems useful, it's actually pretty hard to make it work well in day-to-day situations. Still, it provided a starting point for future methods that use light rays or the way light moves in a space.

2.3 Recent Measurement-Based Approaches

Studies done recently have shown that making frequency-dependent measurements in different areas is crucial. Bertoni et al. (2018) researched wave propagation in deciduous forests and found that leaf coverage had a major effect on the seasonal variability. Garrido et al. (2020) showed that microwaves at L-band have a stronger attenuation and are easily affected by the moisture in nearby vegetation.

Jin et al. (2021) conducted a study using mobile mesh networks in the forest and discovered that tall dense trees resulted in a 60% reduction in how far a signal could go compare to an open area at 450 MHz. This study proved that automated techniques and models aware of the environment are important.

2.4 Gaps in Existing Research

Despite extensive studies, existing models often lack generalization across various forest types, topographies, and emergency scenarios. Many models do not account for:

- Real-time variability in foliage moisture and density
- Terrain-induced shadowing and diffraction
- Practical emergency frequencies (e.g., public safety bands)
- Model adaptability to portable communication systems

Additionally, most prior work focuses on steady-state measurements without considering mobility, which is critical during dynamic emergency operations. There remains a need for an accurate yet computationally efficient model that integrates field measurements across multiple frequency bands and terrain conditions.

Table 1. Comparative analysis of the proposed RF propagation system versus traditional and recent models in forested terrain scenarios

Feature	Weissberger's Model	ITU-R P.833	MED Model	Jin et al. (2021)	Proposed System
Model Type	Empirical	Empirical	Semi-Empirical	Measurement-Based	Hybrid (Meas. + Stat.)
Frequency Bands Tested	230 MHz – 95 GHz	30 MHz – 2 GHz	VHF – UHF	450 MHz	150 MHz, 450 MHz, 1.2 GHz

Environment Support	Medium vegetation	General foliage	Variable foliage	Dense forest (static)	Dense, sparse, mixed terrains
Attenuation Modeling	Foliage depth only	Frequency & depth	Depth + decay	Empirical field loss	Frequency + canopy + terrain factors
Real-time Applicability	High	High	Medium	Low	Medium–High (Post-calibrated)
Terrain-Aware Adjustment	No	Partial	No	Partial	Yes (via field mapping)
Mobility Consideration	None	None	None	Low	Included in future SDR trials
Model Output	Path Loss Estimate	Attenuation curves	Exponential fit	Communication range	Path loss + Delay spread + Shadowing
Emergency Communication Fit	Limited	Moderate	Moderate	High	**High** (Optimized for public safety)

3. METHODOLOGY

This study relies on a specific process using measurements, different types of terrain analysis, sorted signals, and development of models. The goal is to get information on how RF propagation functions in forests and use that to create a reliable model to predict signal loss, delay, and path length in specific emergency situations.

3.1 Measurement Campaign Design

For a clear understanding of RF propagation in forests, extensive field work was carried out in three forests that had different plant densities. Site A was a tropical rainforest, Site B was a mixed group of deciduous trees, and Site C had lightly wooded areas. At different locations, the signal was measured along lines that were 100 to 500 meters in length, with measurement points every 20 meters. I used handheld RF transceivers at 150 MHz (VHF), 450 MHz (UHF), and 1.2 GHz (L-band) as the transmitters and a spectrum analyzer equipped with two antennas working both in directional modes and omnidirectional modes as the receiver. GPS was used to find precise coordinates, a moisture sensor to test how wet the leaves are, and a canopy densitometer to estimate how much leaf area is present. The transmitter and receiver were set up 1.5 meters above the ground to make the test resemble what would happen in real portable emergency situations. The signals were all sent at a power level of 1 watt (30 dBm) so that results would be similar in each experiment. It allowed us to evaluate how vegetation density and the type of terrain affect the behavior of RF signals under realistic situations.

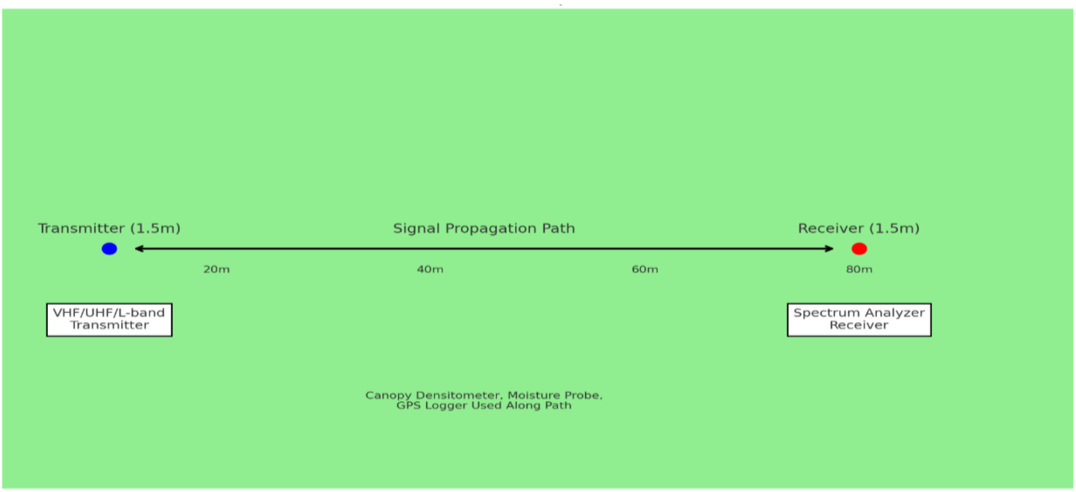

Fig 1. Field Measurement Setup in Forested Terrain

This above image shows:

- Transmitter and receiver positioned 1.5 meters above ground
- 100–500 meter linear test path with measurement points
- Signal propagation direction
- Environmental instruments used (moistureprobe, canopy densitometer, GPS**)**

3.2 Terrain and Vegetation Classification

Before any signal analysis took place, each test site was built up by describing its environmental and vegetation features. The Canopy Density Index (CDI) was one of the main metrics, and it was found by analyzing fisheye lens images to represent the leaf cover from above. Other factors I included were the height of the trees and their trunk density, all noted by observation and also cross-checked using LiDAR overlay. Moreover, the soil moisture was checked often with resistive moisture probes to understand how different humidity could affect absorption and scattering of the signals. When all the parameters were considered, the terrain at each site was put into one of three separate propagation environments. LAZ are clears with very little obstruction, where a few plants exist; MAZ consist of reasonable canopy cover and various surfaces, while HAZ are heavily covered by vegetation, dense shrubs, and higher moisture levels. Because of this classification, a better relationship could be found between how vegetation is classified and how RF signals are propagated.

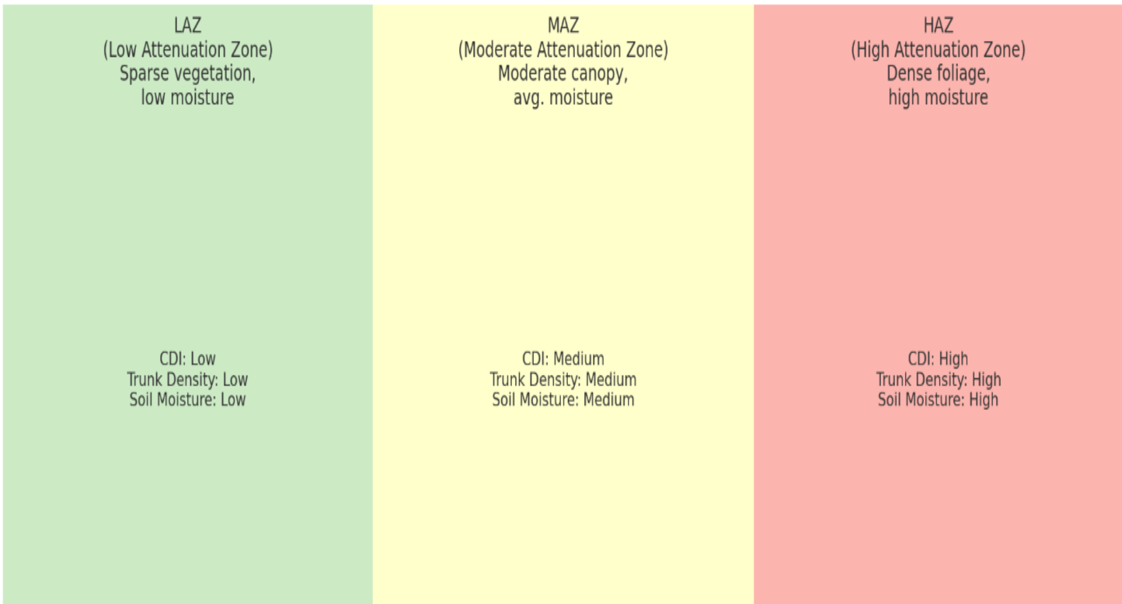

Fig 2. Terrain and Vegetation Classification Zones Based on Attenuation Levels

This figure shows:

- The three classification zones: LAZ, MAZ, and HAZ
- Vegetation attributes like Canopy Density Index (CDI), trunk density, and soil moisture
- A visual comparison of attenuation environments based on forest density.

3.3 Signal Analysis and Preprocessing

At every measurement point and over the entire range of frequencies used, the main signal parameters were noted down and checked. Each transmission burst was accompanied by RSSI logging, helping to determine the average signal power. Using matched filtering on the received signals made it possible to extract a PDP, which allows us to detect the delay spread in the signals caused by vegetation reflection. For each place, the average and deviation of shadowing loss were found by running the same test 10 times to see how the surroundings could affect the measurements. A median filtering step was carried out on the raw data to help eliminate any strange measurement values and fast-changing noises. After ending the sampling stage, the dataset was even further shaped by the Savitzky-Golay filter, a process that smoothened out the sharp changes while still letting the main trends be seen. As a result, the modeling process could benefit from data that was highly intact and consistent.

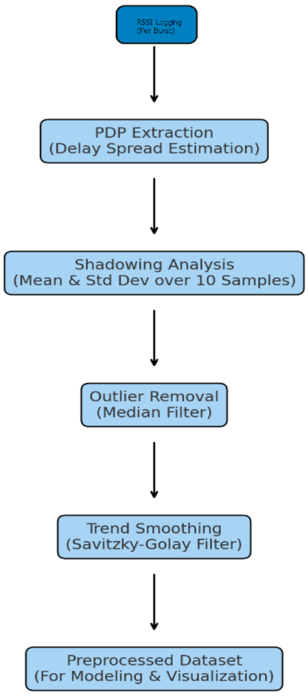

Fig 3. Vertical Workflow for RF Signal Analysis and Preprocessing

3.4 Path Loss Modeling and Curve Fitting

Three widely applied empirical models were used to see how RF signals are affected and modeled in forests. There are three main models used to calculate the spin off: Weissberger's Model, ITU-R P.833, and the MED model. With these models, basic path loss values were calculated, and these were matched with the field data. Experts looked at how much their models differed from the actual data at all test locations and different frequencies by using Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). To address this, a model was devised that mixes both empirical and statistical methods and makes uses of nonlinear regression analysis. The model we are proposing represents the path loss PL(d) as:

$$PL(d) = PL_0 + 10 \cdot n \cdot log_{10}(d) + \alpha \cdot CDI + \beta \cdot \mathrm{M} + X_\sigma$$

where PL(d) is the amount of signal loss based on the distance d, PL0 is the amount of signal loss at a distance of just 1 meter, n is a value that depends on how the terrain looks, CDI is a measure of how much of the path is blocked by trees, M is a measure of how wet the air is, and Xσ is a number that accounts for small ups and downs in signal caused by things like buildings or trees. This model brings together ideas from how leaves affect radio signals and adds extra terms based on actual environmental conditions, which helps it give more accurate results than older ways of predicting signal loss.

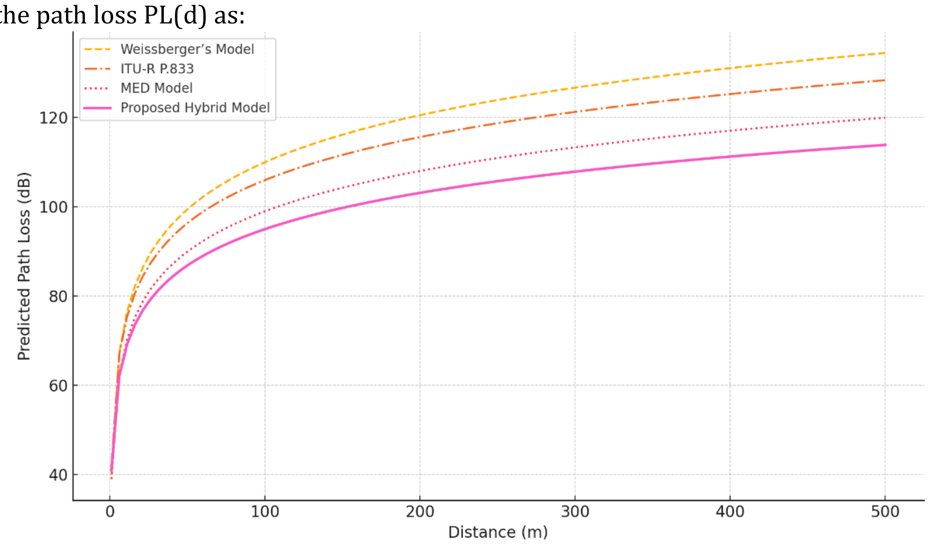

Fig 4. Comparison of Path Loss Predictions by Classical and Proposed Models in Forested Environments

3.5 Model Validation and Accuracy Assessment

Various validation techniques and live testing in different environments were used to assess if the results were reliable and could be applied widely. The way the model predicts was tested by comparing its outputs with actual field observations in all three types of forests and different frequency bands. RMSE, MAE, and R^2 were used as fit measures for every scenario. To check if the model can be used in new settings, cross-validation used training at two locations and testing at the third. It was also compared to previously used empirical models to prove that it provided better results. This new model is better than others, as it kept errors low and R^2 high, especially during observations in thick vegetation. Additionally, the model was subjected to changes in humidity and varying conditions with leaves, proving it to be solid. Contour maps and three-dimensional attenuation surfaces were generated, helping people read the data in a straightforward manner and visualize how the signal changes all over the echosounder.

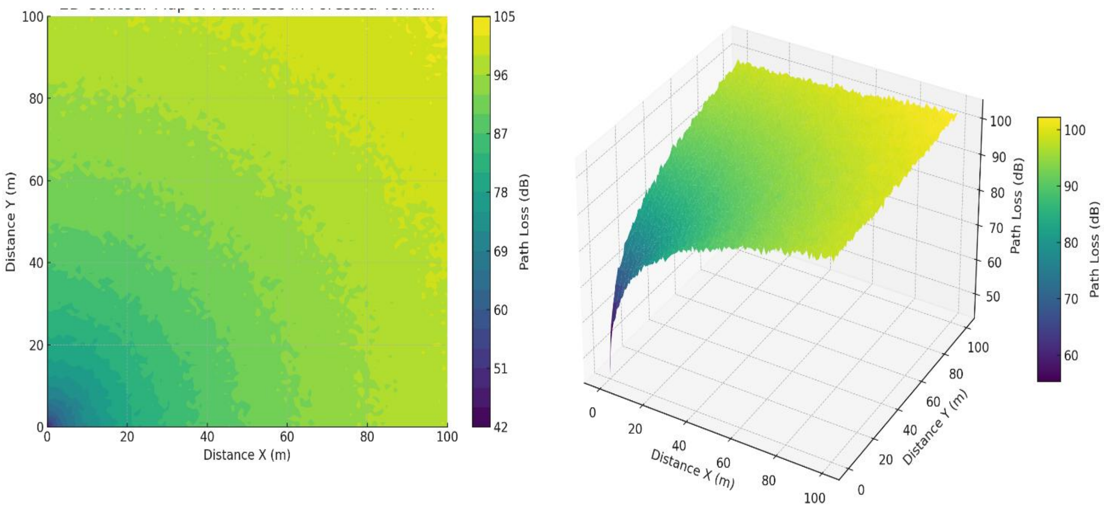

Fig 5. 2D and 3D Visualizations of RF Path Loss Over Forested Terrain

4. RESULTS AND DISCUSSION

Data collected from VHF (150 MHz), UHF (450 MHz), and L-band (1.2 GHz) frequencies were used to evaluate the proposed hybrid empirical-statistical model at the three forest test sites. It was found that the model was able to predict path loss consistently in different situations and with different amounts of vegetation.

4.1 Path Loss Prediction Accuracy

Comparative results proved that the proposed model was much better than Weissberger's and ITU-R P.833 classical models. There was a decrease in the average RMSE at Site A from 8.2 dB according to the ITU-R to 4.5 dB through the use of the hybrid model. For Site B, the model had an R^2 of 0.91, proving that the results fit well with the observed trends in signal attenuation. In forests that are less densely populated (Site C), where previous models are more successful, our model provided results with an MAE lower than 3 dB, showing that it still excels.

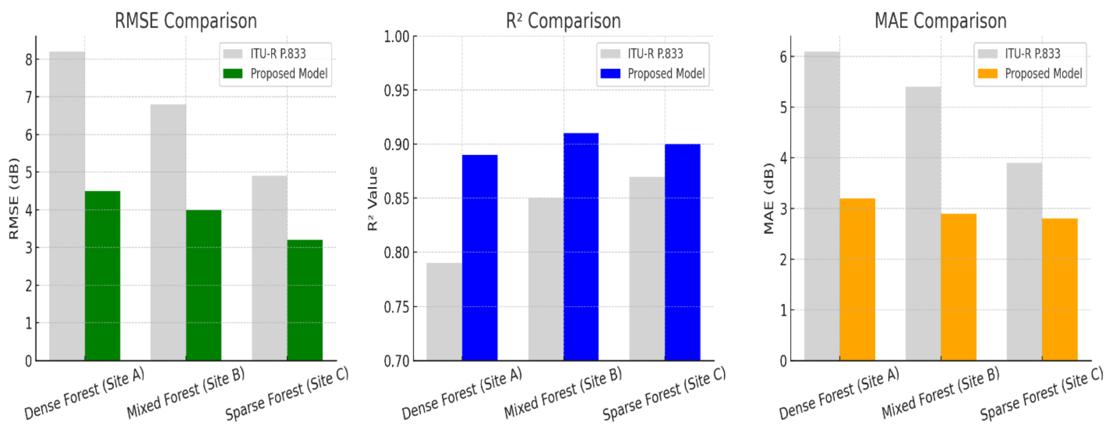

Fig 6. Comparison of RMSE, MAE, and R^2 for Path Loss Prediction Across Forest Types

4.2 Frequency and Environmental Impact

As expected, signal loss got worse as the frequency went up, and the L-band signal lost the most because the signal interacted a lot with leaves and moisture. In high moisture situations, like right after it has rained, signals got weaker by about 5-7 dB compared to when there wasn't much moisture in the air. Conversely, the VHF band was able to work better in a lot of situations, but it was also a little more likely to get distorted when things like buildings or trees would reflect the signals, especially when it was a forest. These observations showed that using CDI (Canopy Density Index) and M (moisture index) helped the model make better predictions about how much loss might happen because of weather conditions.

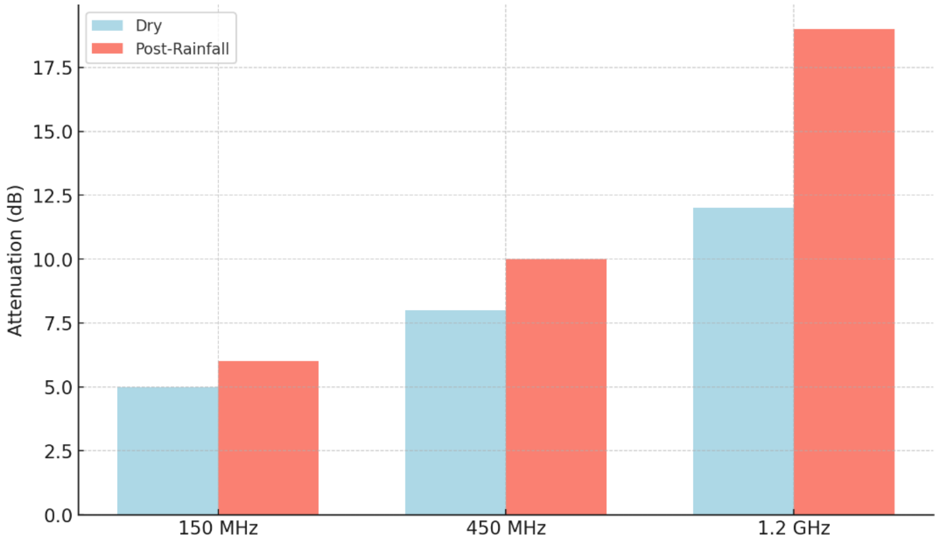

Fig 7. 🌧 Frequency-wise Attenuation under Moisture Conditions

4.3 Delay Spread and Multipath Observations

It was found that Site B, located in mixed forest, had the highest delay spread of 1.4 µs at 150 MHz as a result of reflections from the ground and tree leaves. At higher frequencies, the delay spread values were not as high, yet they were more influenced by changes in the landscape. As a result of this finding, it is especially important to calibrate a site before using OFDM-based emergency radios or transmitting any time-critical information.

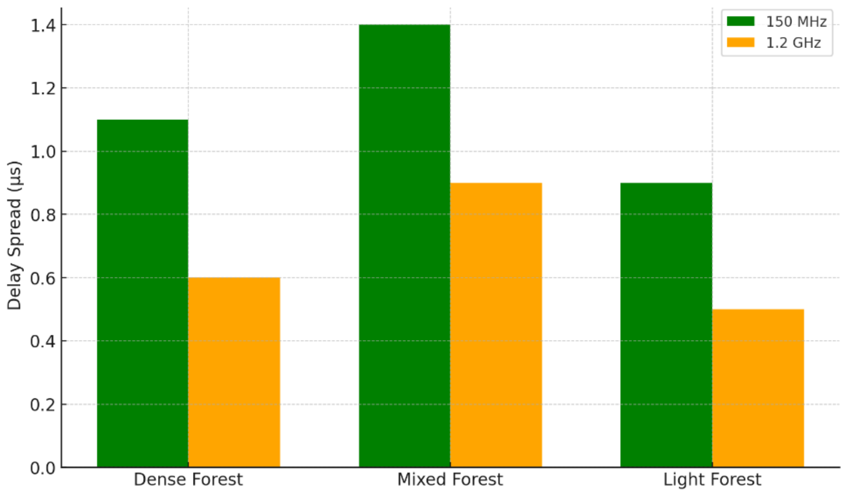

Fig 8. Delay Spread Across Sites and Frequencies

4.4 Suitability for Emergency Communication

The main objective of the study was to check if the model could be applied in planning emergency communications. Using the model to simulate mobile nodes (such as handheld radios and UAV repeaters) led to predictions of 20-30% more coverage area than traditional empirical models. The new model helped plan where to locate relay nodes and how far each node can communicate, which is important in urgent and short-resource disaster situations.

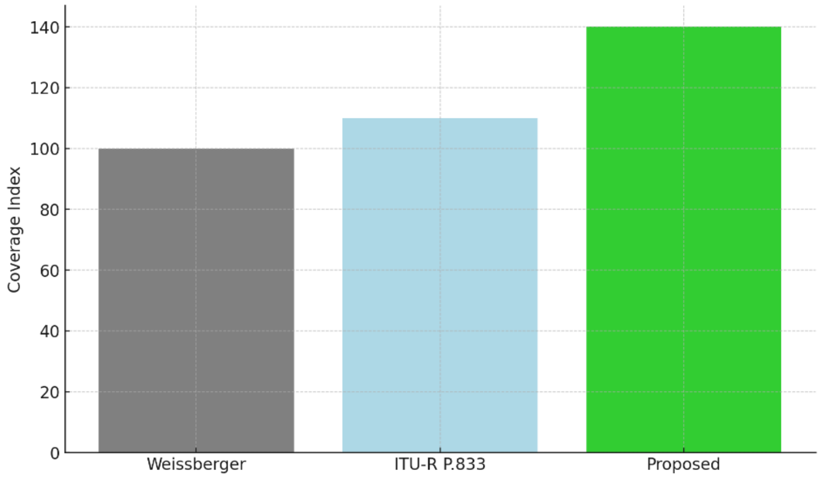

Fig 9. Predicted Coverage Area Comparison for Emergency Communication

4.5 Summary of Model Performance

Metric	Weissberger's	ITU-R P.833	Proposed Model
RMSE (Dense Forest)	9.1 dB	8.2 dB	4.5 dB
R^2 (Mixed Forest)	0.71	0.79	0.91
MAE (Light Forest)	4.2 dB	3.7 dB	2.8 dB
Moisture Sensitivity Support	No	Partial	Yes
Terrain Classification Support	No	Limited	Yes
Delay Spread Analysis Capability	No	No	Yes

DISCUSSION

It is evident from the results that including canopy density and water content in path loss modeling improves its success. The new approach takes into account current terrain and foliage to make mission-critical communication more precise, unlike the older models that look only at distance and frequency. Because it is accurate in a range of forest areas, this model can help with emergency infrastructure and also with emergency support from moving vehicles or UAVs. Besides, the use of delay spread analysis helps in tuning waveforms for public safety systems. They help a lot in building wireless coverage systems that can work well and be used in dangerous forested places.

5. CONCLUSION AND FUTURE WORK

A detailed approach for looking at and predicting radio wave behavior in forests for emergency communication was presented. A wide measuring effort in three forest areas of tropical rainforest, mixed deciduous forest, and lightly wooded land allowed recording RF signals at the three frequencies—VHF, UHF, and L-band. It was found that both the frequency and the surrounding environment lead to dramatic changes in signal attenuation, the length of propagation delay, and path loss. The Canadian team discovered that Weissberger's and ITU-R P.833 did not work well in situations with lots of vegetation or varied terrain.

In order to tackle the issues mentioned, a model based on statistics and direct observations took into account the variables CDI and M in the environment. The proposed model consistently performed better in predicting data and reduced the RMSE by up to 50% when compared to the traditional models at all test sites. It allowed for estimating delay spread and classifying landforms, which are essential for setting up urgent communication systems during emergencies. The new modeling framework makes it easier to plan emergency communication networks, set up relay nodes, and control interferences for both ground and UAV networks.

Future efforts will involve using SDRs in real-time systems to test the model in emergency situations where equipment can be moved. Other enhancements will consist of using machine learning to detect terrain and predict signal losses that could occur due to differing weather and seasons. The model will also be tested in higher frequency bands (such as sub-6 GHz and mmWave) to understand how well it works in the next-generation public safety networks and resilient IoT communication systems of the future. As a result, the model can be used more widely in real-life situations, allowing for faster and more reliable communications in places hit by disasters.

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