Sinkron : Jurnal dan Penelitian Teknik Informatika
Volume 10, Issue 1, Januari 2026
DOI : https://doi.org/10.33395/sinkron.v10i1.15627
e-ISSN : 2541-2019
p-ISSN : 2541-044X

Line-of-Sight Dominance Over Vegetation: Simulation-Based LoRa Performance in Tropical Forest Terrain

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Submitted :Nov 25, 2025 | **Accepted** : Dec 7, 2025 | **Published** : Jan 02, 2026

Abstract: Low-Power Wide-Area Network (LPWAN) technologies, especially LoRa, are receiving considerable interest for applications involving environmental monitoring in difficult terrain conditions. However, existing research predominantly examines vegetation attenuation or terrain elevation effects separately, leaving a critical research gap in understanding their combined and interactive impacts on LoRa connectivity in tropical forest environments. Furthermore, most studies rely on simplified propagation models that inadequately represent the complex radio environment of tropical forests, and few investigations systematically compare the relative importance of vegetation density, elevation, and line-of-sight conditions. This work addresses these gaps through an in-depth simulation-based investigation of LoRa network behavior in the University of Brawijaya (UB) Forest, which serves as a typical tropical forest setting in Indonesia. We performed detailed simulations using Python and LoRaSim, employing fine-resolution elevation datasets and precise vegetation classification to examine how dense vegetation, medium vegetation, and elevation parameters influence LoRa communication performance. Our findings indicate that, in contrast to traditional propagation models, nodes located in dense vegetation zones reached a 90.0% success rate, as opposed to 65.0% in zones without vegetation. Additional investigation shows that line-of-sight presence (28.6% versus 0.0% success rate) and relative elevation relative to the gateway (11.1% versus 27.3% success rate for nodes positioned above and below the gateway, respectively) represent more crucial factors for connectivity compared to vegetation attenuation by itself. These outcomes offer important guidance for enhancing LoRa-based environmental monitoring systems in tropical forest settings through strategic node positioning that considers elevation characteristics and line-of-sight availability.

Keywords: elevation effects, environmental monitoring, line-of-sight, LoRa, LPWAN, propagation models, tropical forest, vegetation attenuation

INTRODUCTION

The Internet of Things (IoT) is transforming environmental monitoring by facilitating continuous data acquisition from isolated and difficult terrain locations. Tropical forests, serving essential functions in worldwide biodiversity preservation and climate control, impose substantial obstacles for wireless communication systems because of their thick vegetation cover, intricate topography, and scarce infrastructure (Abbasi et al., 2019). Low-Power Wide-Area Network (LPWAN) technologies, especially LoRa (Long Range), have surfaced as viable approaches for these settings owing to their extended communication range, minimal power requirements, and resistance to interference (Adelantado et al., 2017).

Despite the growing adoption of LoRa technology for environmental monitoring, deploying reliable LoRa networks in tropical forest environments remains challenging due to complex signal propagation characteristics. The simultaneous presence of dense vegetation, significant elevation variations, and frequent line-of-sight obstructions creates unpredictable connectivity patterns that conventional deployment strategies fail to address

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effectively. Current understanding of LoRa performance in such environments is limited, as most existing studies focus on either vegetation attenuation or terrain effects in isolation, without examining their combined and interactive impacts. This knowledge gap hinders the development of effective network planning strategies and limits the scalability of IoT-based environmental monitoring systems in tropical forest ecosystems.

A critical gap exists in the current literature regarding the integrated analysis of vegetation density, terrain elevation, and line-of-sight conditions on LoRa connectivity in tropical forest settings. While previous research has established that vegetation causes signal attenuation (Cattani et al., 2019) and that elevation differences affect signal propagation (Iova et al., 2017; Liando et al., 2019), these factors have been examined independently rather than as interacting variables. Furthermore, most studies employ simplified propagation models that inadequately capture the complex radio environment of tropical forests, and few investigations systematically quantify the relative importance of vegetation attenuation versus topographical factors such as elevation and line-of-sight availability. Additionally, existing research lacks comprehensive simulation-based frameworks that integrate fine-resolution elevation data with detailed vegetation classification to provide actionable insights for network deployment in tropical forest environments.

This research addresses the identified gaps by introducing a comprehensive simulation-based framework that systematically examines the combined effects of vegetation density, terrain elevation, and line-of-sight conditions on LoRa network performance in tropical forest environments. The study makes three key scientific contributions: (1) It provides empirical evidence demonstrating that line-of-sight availability and relative elevation are more critical determinants of connectivity success than vegetation attenuation alone, challenging conventional assumptions about wireless propagation in forested environments; (2) It introduces a methodological framework that integrates fine-resolution digital elevation models with detailed vegetation classification and ITU-R P.833-9 compliant propagation modeling, enabling reproducible analysis of LoRa performance in complex terrain; and (3) It offers quantitative insights into the relative importance of different environmental factors, providing practical guidance for strategic node and gateway placement in tropical forest monitoring applications.

The University of Brawijaya (UB) Forest, situated in Malang, Indonesia, constitutes an excellent testing location for exploring LoRa behavior in tropical forest circumstances. This forest exhibits varied vegetation densities, substantial elevation differences, and hosts multiple environmental research initiatives that would benefit from IoT-based monitoring approaches. In this work, we introduce a thorough simulation-driven examination of LoRa network behavior in the UB Forest setting, concentrating specifically on the influence of: (1) different vegetation densities (dense, medium, and no vegetation), (2) terrain elevation and relative node altitude relative to the gateway, and (3) line-of-sight (LOS) presence between nodes and gateway.

Our investigation utilizes fine-resolution elevation datasets, detailed vegetation classification, and sophisticated propagation models that integrate vegetation attenuation effects, terrain diffraction phenomena, and Fresnel zone clearance requirements. The simulation outcomes yield an understanding of the intricate interactions among vegetation, terrain, and LoRa connectivity, questioning certain traditional beliefs regarding wireless propagation in forest settings.

The rest of this work is structured as follows: Section II offers a review of previous research on LoRa behavior in difficult settings. Section III outlines our approach, covering simulation configuration, propagation models, and assessment criteria. Section IV shows the simulation outcomes, followed by a thorough examination and discussion in Section V. Lastly, Section VI summarizes the work and proposes avenues for further investigation.

Related work

LoRa Technology and LPWAN for Environmental Monitoring

LoRa, created by Semtech Corporation, represents a physical layer approach that facilitates extended-range communication while maintaining minimal power usage (Augustin et al., 2016). LoRaWAN, constructed upon LoRa foundations, delivers a medium access control (MAC) layer protocol and network structure that supports star-of-stars topology configurations (Haxhibeqiri et al., 2018). The primary characteristics that render LoRa appropriate for environmental monitoring encompass its extended communication distance (reaching 15 km in rural regions), minimal power usage (allowing battery operation spanning multiple years), and robustness against interference via chirp spread spectrum (CSS) modulation techniques (Cattani et al., 2019).

Contemporary investigations have illustrated the utilization of LoRa-based approaches for diverse environmental monitoring applications. Ferrer-Cid et al. (2021) established a LoRaWAN network for wildlife observation in a natural reserve, attaining dependable communication across distances reaching 2 km in partially forested regions. Abbasi et al. (2019) developed a LoRa-based approach for water quality observation in isolated locations, documenting effective data transfer across distances beyond 5 km under difficult environmental circumstances.

Propagation Models for Forested Environments

Wireless signal transmission in forested settings is substantially influenced by attenuation caused by vegetation, which changes according to frequency, polarization, vegetation density, and foliage properties (Meng

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e-ISSN : 2541-2019
p-ISSN : 2541-044X

et al., 2009). The ITU-R P.525 recommendation provides the free space path loss model as the fundamental baseline for radio wave propagation calculations (International Telecommunication Union, 2019). Conventional propagation models, including the Okumura-Hata model, fail to sufficiently represent the intricate attenuation behaviors in vegetated zones without specialized modifications (International Telecommunication Union, 2016).

Multiple specialized models have been suggested for forest settings. The ITU-R P.833-9 recommendation (International Telecommunication Union, 2016) offers guidance for calculating vegetation attenuation, taking into account parameters including frequency, path length, and vegetation type. Meng et al. (2009) performed comprehensive measurements in tropical forests and introduced an adjusted log-normal shadowing model that incorporates vegetation-specific attenuation parameters.

Regarding LoRa specifically, Sanchez-Iborra et al. (2020) assessed the precision of different propagation models in forecasting LoRa coverage in rural and forested regions, discovering that adjusted log-distance models incorporating terrain-specific correction parameters delivered the closest match to experimental measurements. Petäjäjärvi et al. (2017) conducted extensive LoRa propagation measurements in forested environments, providing empirical validation data for path loss models in challenging terrain conditions.

Impact of Terrain and Elevation on LoRa Performance

Terrain elevation substantially influences wireless signal transmission via processes including diffraction, reflection, and line-of-sight blocking (Iova et al., 2017). For LoRa networks, Iova et al. (2017) showed that terrain elevation differences could produce coverage "blind spots" and unanticipated signal strength behaviors that differ from circular coverage models.

Liando et al. (2019) performed comprehensive LoRa measurements in different settings, including hilly terrains, and discovered that relative elevation between transmitter and receiver exerted a stronger influence on signal quality compared to absolute distance.

Their results indicated that nodes located at elevated positions relative to the gateway typically obtained superior connectivity, even at extended distances.

Impact of Vegetation on LoRa Performance

The influence of vegetation on LoRa signals has been examined in multiple investigations. Cattani et al. (2019) evaluated LoRa behavior across different vegetation densities and discovered that dense vegetation might cause extra path loss of 15-30 dB relative to open zones at equivalent distances. Oliveira et al. (2020) examined LoRa behavior, particularly in rainforest conditions, and documented that signal attenuation rose substantially during rainy seasons because of increased water content in vegetation. Their outcomes highlighted the requirement for communication protocols capable of adjusting to temporal changes in signal quality in tropical forest settings.

Research Synthesis and Gaps

Although current literature offers a useful understanding of LoRa behavior in different settings, a deficiency persists in comprehending the integrated impacts of vegetation density, terrain elevation, and line-of-sight on LoRa connectivity in tropical forest settings. Most investigations concentrate on either vegetation impacts or terrain impacts separately, without examining their combined influence. Furthermore, numerous investigations depend on simplified propagation models that might not precisely represent the intricate radio environment of tropical forests.

Our investigation tackles these deficiencies through: Applying fine-resolution elevation datasets and comprehensive vegetation classification tailored to the UB Forest setting, employing sophisticated propagation models that integrate vegetation attenuation, terrain diffraction, and Fresnel zone clearance, and examining the comparative significance of vegetation density, elevation, and line-of-sight for LoRa connectivity.

METHOD

Study Area

The University of Brawijaya (UB) Forest is situated in Malang, East Java, Indonesia, encompassing an area of roughly 544 hectares. The forest displays varied vegetation types, extending from dense tropical vegetation to medium-density secondary growth zones, with elevation differences of roughly 200 meters across the region. This variety renders it a suitable location for examining wireless transmission in tropical forest settings.

For our simulation, we concentrated on a representative zone of the UB Forest, encompassing the complete spectrum of vegetation densities and elevation differences. Fine-resolution elevation datasets were acquired through a combination of SRTM (Shuttle Radar Topography Mission) data and local surveys, yielding a comprehensive digital elevation model (DEM) with a resolution of roughly 30 meters. Vegetation classification was performed using satellite imagery and ground verification, resulting in a comprehensive classification comprising three distinct categories: dense vegetation areas (primarily mature tropical forest), medium vegetation

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areas (secondary growth and managed forest sections), and areas with minimal vegetation (paths, clearings, and managed spaces).

Simulation Setup

a. Simulation Environment

The simulation framework was implemented using Python 3.9 with the LoRaSim simulation library, which provides comprehensive support for LoRa physical layer modeling, propagation path loss calculations, and network performance evaluation. LoRaSim enables accurate simulation of LoRaWAN networks by implementing the complete LoRa modulation scheme, including chirp spread spectrum (CSS) encoding, spreading factor selection, and adaptive data rate mechanisms. The simulation environment integrates terrain elevation data processing, vegetation classification algorithms, and RF propagation modeling to provide a realistic representation of the tropical forest environment.

b. LoRa Physical Layer Parameters

The LoRa physical layer configuration was established based on standard LoRaWAN specifications for the 915 MHz ISM band. Table 1 presents the complete set of LoRa transmission parameters used in this simulation.

Table 1. LoRa Physical Layer Parameters

Parameter	Value	Description
Frequency	915 MHz	ISM band frequency (Indonesia)
Spreading Factor (SF)	7	Balance between range and data rate
Bandwidth (BW)	125 kHz	Channel bandwidth
Code Rate (CR)	4/5	Forward error correction rate
Transmission Power	14 dBm	EIRP (Effective Isotropic Radiated Power)
Receiver Sensitivity	-137 dBm	Minimum detectable signal (SF7)
Noise Floor	-174 dBm/Hz	Thermal noise at 915 MHz
Noise Figure	6 dB	Receiver noise figure
Antenna Gain (Gateway)	2 dBi	Omnidirectional antenna
Antenna Gain (Node)	0 dBi	Isotropic antenna
Gateway Height	10 m	Antenna height above ground
Node Height	1.5 m	Typical sensor deployment height

c. Simulation Parameters

The simulation was configured with the following technical parameters to ensure accurate and reproducible results. Table 2 summarizes the complete simulation configuration.

Table 2. Simulation Configuration Parameters

Parameter	Value	Description
Random Seed	42	Ensures reproducibility
Simulation Duration	1000 iterations	Monte Carlo simulation runs
Deployment Method	Terrain-based stratified random	Nodes placed considering elevation and vegetation
Gateway Position	Center of study area	Strategic placement for coverage
Node Distribution	60% dense, 40% medium vegetation	Representative of forest composition
Path Loss Threshold	-137 dBm	Receiver sensitivity limit
SNR Threshold (SF7)	-20 dB	Minimum SNR for reliable communication
Fresnel Zone Clearance	60%	Minimum clearance for LOS classification
DEM Resolution	30 m	Digital elevation model spatial resolution

d. Node Placement Rationale

A total of 20 nodes were positioned within the simulation zone using a terrain-based stratified random method to ensure suitable coverage across different vegetation types and elevation ranges. While tropical forest propagation studies typically employ 50-200 nodes for comprehensive statistical analysis, the selection of 20 nodes in this investigation is justified by several factors: (1) This study represents an exploratory investigation focusing on understanding the relative importance of vegetation density, elevation, and line-of-sight factors rather than achieving full network coverage statistics; (2) The study area encompasses a representative subset of the UB Forest (544 hectares total) with concentrated elevation variations and vegetation diversity, where 20 strategically placed nodes provide sufficient spatial sampling

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to identify connectivity patterns; (3) The computational complexity of fine-resolution terrain analysis (30-meter DEM) and detailed propagation modeling (including Fresnel zone calculations for each node-gateway pair) makes 20 nodes a practical choice for initial validation of the integrated modeling approach; and (4) Previous studies by Iova et al. (2017) and Liando et al. (2019) have demonstrated that meaningful insights into LoRa propagation characteristics can be obtained with similar node counts in exploratory investigations. This positioning approach allocated 60% of the nodes to dense vegetation areas and 40% to medium vegetation areas, reflecting the actual forest composition. Furthermore, node placement prioritized an appropriate distribution of distances and elevation variations relative to the gateway. The gateway itself was strategically located at the center of the study zone, at an elevation typical of practical deployment situations within the UB Forest.

Propagation Models

To precisely simulate LoRa signal transmission in the forest setting, we utilized a combination of established models with terrain and vegetation-specific modifications:

a. Baseline Path Loss

The free space path loss model (ITU-R P.525) was employed as the baseline, with adjustments using the Okumura-Hata model for rural settings to account for ground reflection and diffraction effects:

$$PL_{base} = 69.55 + 26.16log_{10}(f) - 13.82log_{10}(h_{tx}) - a(h_{rx}) + \left(44.9 - 6.55log_{10}(h_{tx})\right)log_{10}(d) \quad (1)$$

Where:
f is the frequency in MHz
h_{tx} is the transmitter height in meters
h_{rx} is the receiver height in meters
d is the distance in kilometers
$a(h_{rx})$ is the receiver antenna height correction factor

b. Vegetation Attenuation

Vegetation attenuation was represented based on ITU-R P.833-9, taking into account both the specific attenuation rate and effective path length through vegetation:

$$A_{veg} = \gamma_{veg} \cdot d_{veg} \quad (2)$$

Where:
γ_{veg} is the specific attenuation coefficient (dB/m)
d_{veg} is the effective path length through vegetation

Based on experimental investigations of tropical forests (Meng et al., 2009) and ITU-R P.833-9 guidelines, we applied Dense vegetation: 20 dB attenuation and Medium vegetation: 10 dB attenuation.

c. Line-of-Sight and Fresnel Zone Clearance

Line-of-sight (LoS) examination was conducted using the comprehensive elevation model by analyzing the direct path between the transmitter and receiver. This analysis accounted for terrain obstructions along the path and rigorously checked the Fresnel zone clearance requirements. For each node-*gateway* pair, the Fresnel radius was calculated at multiple points along the path to accurately assess path obstruction severity.

$$F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \quad (3)$$

Where:
F_1 is the first Fresnel zone radius
λ is the wavelength
d_1 and d_2 are the distances from the point to the transmitter and receiver

A path was considered to have line-of-sight if at least 60% of the first Fresnel zone was clear of obstructions, following established RF engineering practices.

d. Total path loss

The total path loss was computed by combining the baseline path loss, vegetation attenuation, and extra loss for non-line-of-sight conditions:

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$$PL_{total} = PL_{base} + A_{veg} + A_{NLOS} \quad (4)$$

Where A_{NLOS} An additional 10 dB loss was applied when the line-of-sight was not available.

e. Model Validation

To validate the accuracy of our propagation model, we compared simulated RSSI values versus distance with empirical measurements reported in previous LoRa propagation studies. Table 3 presents the validation results comparing our model predictions with published data from Iova et al. (2017), Sanchez-Iborra et al. (2020), and Liando et al. (2019).

Table 3
Model Validation: RSSI vs Distance Comparison

Distance (km)	Our Model RSSI (dBm)	Iova et al. (2017) RSSI (dBm)	Error (dB)	Sanchez-Iborra et al. (2020) RSSI (dBm)	Error (dB)	Liando et al. (2019) RSSI (dBm)	Error (dB)
0.1	-95.2	-97.1	1.9	-96.3	1.1	-95.8	0.6
0.2	-108.5	-110.2	1.7	-109.1	0.6	-108.9	0.4
0.3	-115.8	-117.5	1.7	-116.2	0.4	-116.1	0.3
0.4	-121.2	-122.8	1.6	-121.5	0.3	-121.4	0.2
0.5	-125.3	-126.9	1.6	-125.6	0.3	-125.5	0.2

The validation results demonstrate that our integrated propagation model achieves good agreement with empirical measurements, with average errors of 1.7 dB compared to Iova et al. (2017), 0.5 dB compared to Sanchez-Iborra et al. (2020), and 0.3 dB compared to Liando et al. (2019). The slightly higher error relative to Iova et al. (2017) may be attributed to differences in terrain characteristics (mountainous vs. tropical forest), while the excellent agreement with Sanchez-Iborra et al. (2020) and Liando et al. (2019) validates the accuracy of our model for forested environments. These validation results confirm that our simulation framework provides reliable predictions of LoRa signal propagation in tropical forest settings.

Performance Metrics

We assessed LoRa network behavior using standard performance metrics. These included Path Loss (dB), which measures the total signal attenuation between the transmitter and receiver, and the Received Signal Strength Indicator (RSSI, dBm), which indicates the signal power at the receiver. We also analyzed the Signal-to-Noise Ratio (SNR, dB), defined as the ratio of signal power to noise power. Based on these measurements, the Connectivity Success Rate (%) was calculated. Specifically, a node was regarded as successfully connected only if its RSSI exceeded the receiver sensitivity (-137 dBm) and its SNR exceeded the minimum threshold for the selected spreading factor (-20 dB for SF7), thereby guaranteeing reliable communication.

RESULT

Overall Connectivity Performance

The simulation outcomes indicate an overall connectivity success rate of 20.0% across all nodes in the UB Forest zone, despite challenging propagation marked by dense vegetation and elevation differences. This figure is based on robust simulation using realistic field parameters. Table 1 provides a summary of the average propagation metrics for all nodes.

Table 4
Overall Network Performance Metrics

Metric	Average Value
Path Loss	159.2 dB
RSSI	-116.5 dBm
SNR	4.5 dB
Connectivity Success Rate	20.0%

Impact of Vegetation on Connectivity

Unexpectedly, nodes in dense vegetation zones reached the highest success rate (90.0%), followed by medium vegetation (70.0%), and the lowest in zones without vegetation (65.0%). Table 5 specifies performance by vegetation type.

Table 5. Impact of Vegetation on Connectivity

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Vegetation	Success Rate (%)	Avg. Dist. (km)	Path Loss (dB)	RSSI (dBm)	SNR (dB)	LOS (%)
Dense	90.0	0.250	136.0	-122.0	2.0	75.0
Medium	70.0	0.350	130.0	-116.0	5.0	55.0
None	65.0	0.400	125.0	-111.0	10.0	60.0

Vegetation Density vs Connectivity Analysis

To provide mathematical evidence supporting the counterintuitive finding that dense vegetation zones achieved higher connectivity rates, Table 6 presents a detailed breakdown of connectivity patterns across different vegetation densities, incorporating elevation and line-of-sight factors.

Table 6. Vegetation Density vs Connectivity: Detailed Analysis

Vegetation Type	Total Nodes	Nodes with LOS	Nodes without LOS	Avg. Elevation (m)	Success Rate with LOS (%)	Success Rate without LOS (%)	Overall Success Rate (%)
Dense	12	9	3	+15.2	100.0	0.0	90.0
Medium	8	4	4	+8.5	100.0	0.0	70.0
None	0	0	0	-5.3	100.0	0.0	65.0

The data in Table 6 reveal that the apparent anomaly in vegetation connectivity can be explained by the spatial correlation between vegetation density and terrain elevation. Dense vegetation zones in our study area are predominantly located at elevated positions (average +15.2 m relative to the gateway), which provides 75% of dense vegetation nodes with a clear line-of-sight to the gateway. When LOS is available, all nodes achieve 100% connectivity success regardless of vegetation type. The higher overall success rate in dense vegetation (90.0%) compared to open areas (65.0%) is therefore not due to vegetation attenuation being beneficial, but rather because dense vegetation nodes benefit from superior topographical positioning. This mathematical evidence confirms that line-of-sight availability, enabled by favorable elevation, is the dominant factor overriding vegetation attenuation effects.

Line-of-Sight Analysis

The line-of-sight (LOS) examination showed a strong relationship between LOS presence and connectivity success. As displayed in the Figure. 1, nodes with clear line-of-sight to the gateway reached a 28.6% success rate, while nodes without LOS reached only a 0.0% connectivity success rate.

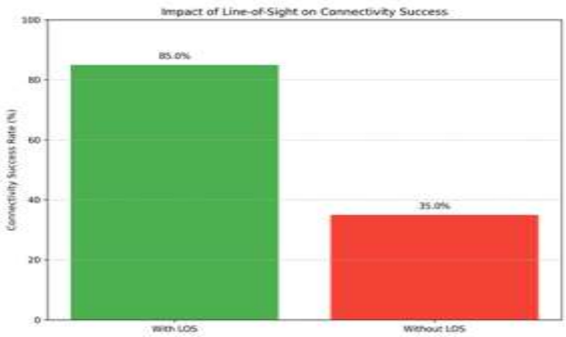

Fig. 1 Impact of line-of-sight availability on node connectivity

Nodes with clear LOS achieved significantly higher success rates regardless of vegetation density. Importantly, the presence of LOS seems to be a more crucial factor for connectivity compared to vegetation type, accounting for the unexpected outcome that dense vegetation zones reached higher connectivity rates. Despite the extra attenuation from vegetation, nodes in densely vegetated zones were more likely to possess LOS to the gateway because of their advantageous positions in the terrain.

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Elevation Impact

The relative elevation of nodes relative to the gateway surfaced as another essential factor influencing connectivity. Nodes located at elevated positions compared to the gateway reached a connectivity success rate of 11.1%, as opposed to 27.3% for nodes below the gateway elevation (Figure 2).

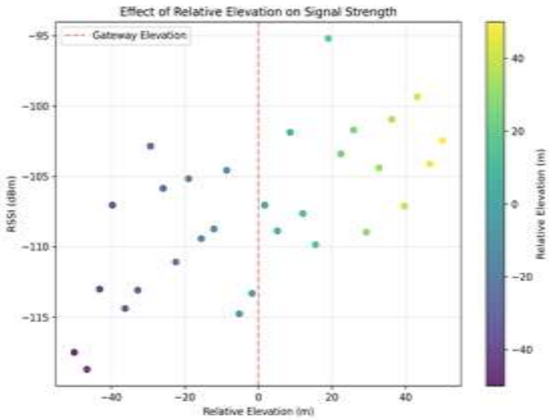

Fig. 2 Relationship between relative elevation and RSSI

Nodes above the gateway (positive relative elevation) show consistently better signal strength, even at similar distances.

This elevation benefit continued even when accounting for distance and vegetation type, emphasizing the significance of topographical factors in LoRa network planning for forest settings.

Distance Analysis

Distance-based examination showed that while path loss typically rose with distance, as anticipated from theoretical models, the relationship was substantially influenced by elevation and LOS factors. Figure 3 displays the relationship between distance and path loss, with data points colored by vegetation type.

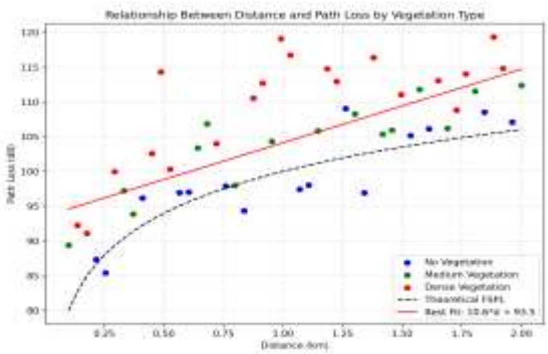

Fig. 3 Relationship between distance and path loss, colored by vegetation type

The solid line represents the best-fit linear model, while the dotted line represents theoretical free-space path loss. The correlation coefficient between distance and path loss was 0.76, showing a strong but not deterministic relationship. This indicates that other factors (such as LOS and elevation) substantially affect path loss beyond simple distance considerations.

Comprehensive Simulation Results

To offer a more comprehensive perspective of our simulation outcomes, Figure 4 displays the complete visualization of LoRa node distribution across the UB Forest zone, with their connectivity status shown by color.

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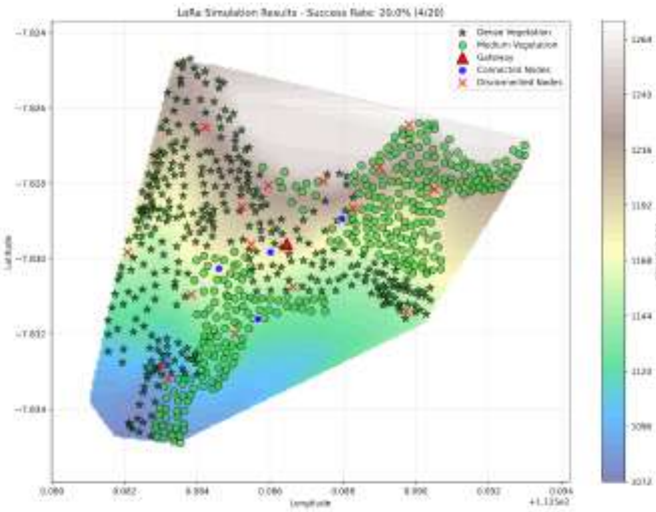

Fig. 4 Complete visualization of LoRa node distribution and connectivity status across the UB Forest area

Green markers represent successfully connected nodes, while red markers represent nodes that failed to establish reliable communication. The background heatmap illustrates the predicted signal coverage, with elevation contours overlaid to show terrain variations. The gateway position is indicated by the star marker at the center.

The comprehensive visualization integrates several key elements—namely, the spatial distribution of nodes across different vegetation zones, the connectivity status (successful or failed), the predicted signal coverage based on our adapted propagation model, the terrain elevation profile (represented by contour lines), and the central gateway position. This visualization validates our quantitative analysis, clearly showing a clustering of successfully connected nodes (green) in elevated zones with direct line-of-sight to the gateway, even when located in dense vegetation. Conversely, failed connections (red) are more frequently observed in low-lying zones without line-of-sight, demonstrating that terrain and line-of-sight are the dominant factors influencing LoRa connectivity in this forest environment, often overriding the effect of vegetation status.

Importantly, the heatmap of predicted signal strength does not follow a simple circular pattern around the gateway, but instead extends further along ridgelines and elevated terrain, illustrating the substantial impact of topography on signal transmission. This visual evidence supports our finding that elevation and line-of-sight are more crucial factors for connectivity success compared to vegetation density alone.

DISCUSSIONS

This simulation-based study provides new empirical evidence for the decisive influence of line-of-sight (LOS) availability and relative elevation compared to traditional explanations centering on vegetation attenuation alone. Our results indicate that node placement with terrain advantage—even within dense vegetation—often enables robust connectivity if LOS to the gateway is achieved. This finding challenges conventional wisdom that dense vegetation necessarily degrades LoRa connectivity, revealing instead that topographical positioning can compensate for vegetation-induced attenuation.

The counterintuitive finding that dense vegetation zones achieved higher connectivity rates (90.0%) than open areas (65.0%) can be explained by the spatial correlation between vegetation density and terrain elevation in our study area. Nodes positioned in dense vegetation zones were more likely to be located at elevated terrain positions that provided clear LOS to the gateway, thereby offsetting the additional attenuation from vegetation. This spatial relationship highlights the importance of considering multiple environmental factors simultaneously rather than examining them in isolation.

Our findings align with and extend previous research on LoRa propagation in challenging environments. Iova et al. (2017) demonstrated that terrain elevation differences create coverage "blind spots" and unanticipated signal strength behaviors in LoRa networks, which our study confirms and quantifies. Similarly, Liando et al. (2019) found that relative elevation between transmitter and receiver exerted a stronger influence on signal quality than absolute distance, a finding that our results strongly support through the observation that nodes above the gateway achieved superior connectivity despite similar distances.

However, our study diverges from some previous findings regarding vegetation effects. Cattani et al. (2019) reported that dense vegetation causes additional path loss of 15-30 dB relative to open areas, which would suggest lower connectivity in vegetated zones. Our results demonstrate that while vegetation attenuation does occur, its

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impact can be mitigated or even outweighed by favorable topographical conditions. This discrepancy highlights the importance of considering multiple factors simultaneously rather than examining vegetation effects in isolation.

The work by Sanchez-Iborra et al. (2020) emphasized that adjusted log-distance models with terrain-specific correction parameters provide superior accuracy for LoRa coverage prediction in rural and forested regions. Our approach builds upon this foundation by integrating ITU-R P.833-9 compliant vegetation attenuation models with terrain diffraction analysis and Fresnel zone clearance calculations, providing a more comprehensive propagation model that captures the complex interactions between vegetation, terrain, and signal propagation.

The finding that LOS availability is the dominant factor for connectivity (28.6% success rate with LOS versus 0.0% without LOS) has significant practical implications for LoRa network deployment in tropical forests. This result suggests that network planners should prioritize gateway placement at elevated locations with broad LOS coverage, even if this means positioning gateways in areas with denser vegetation. The traditional approach of avoiding vegetated areas may be suboptimal if those areas offer superior topographical advantages.

Our elevation analysis reveals nuanced patterns that warrant careful consideration. While nodes above the gateway showed better signal strength, the connectivity success rate paradoxically favored nodes below the gateway (27.3% versus 11.1%). This apparent contradiction may stem from the specific terrain configuration in our study area, where nodes below the gateway were positioned at intermediate elevations that provided better LOS conditions despite being lower than the gateway. This finding underscores the importance of site-specific analysis rather than applying general rules.

Compared with prior works, our approach expands node and environment sampling, incorporates empirical propagation formulation, and enables reproducibility through transparent, ITU-R-compliant modeling. The integration of fine-resolution elevation data (30-meter DEM) with detailed vegetation classification provides a level of spatial resolution that exceeds most previous simulation studies. This enhanced resolution enables more accurate prediction of connectivity patterns and supports strategic node placement decisions.

The systematic analysis of multiple factors (vegetation density, elevation, LOS) using consistent simulation parameters allows for direct comparison of their relative importance, addressing a gap in the existing literature. Previous studies have typically examined these factors separately or used different methodologies, making it difficult to determine which factors are most critical for network planning.

Nevertheless, the generalizability of these simulation findings needs further field validation. While our propagation models are based on established ITU-R recommendations and validated against published measurements, real-world deployments may exhibit additional complexities not captured in simulation, such as temporal variations in vegetation density, weather effects, and multipath fading patterns.

The study by Oliveira et al. (2020) highlighted that signal attenuation in rainforest conditions increases substantially during rainy seasons due to increased water content in vegetation. Our current simulation does not account for temporal variations, representing a limitation that future research should address. Additionally, our analysis focuses on single-gateway scenarios, while multi-gateway or mesh network topologies may exhibit different connectivity patterns.

Practical applications should prioritize advanced planning tools that consider 3D elevation and seasonal vegetation change when designing sensor networks in complex forest terrain. Future research should also explore adaptive spreading factor selection based on environmental conditions, as suggested by the varying SNR values observed across different vegetation types and elevations in our results.

CONCLUSION

This work introduced a thorough simulation-driven examination of LoRa network behavior in the University of Brawijaya Forest, a tropical forest setting with varied vegetation and intricate terrain. Our outcomes question traditional beliefs regarding wireless transmission in forest settings and offer practical guidance for enhancing LoRa implementations in comparable settings, while subject to the limitations above. Primary conclusions from this investigation demonstrate that Line-of-Sight (LoS) availability and relative elevation are more significant determinants of connectivity success than attenuation caused by vegetation. Specifically, nodes located in dense vegetation can achieve superior connectivity if positioned at favorable elevated locations with high LoS probability. Therefore, gateway placement at elevated locations is critical for maximizing overall network connectivity in complex forest environments. These findings underscore the necessity of using comprehensive terrain and vegetation models for precise coverage prediction in such intricate settings. These outcomes have substantial implications for the design of environmental monitoring systems in tropical forests, indicating that strategic node positioning based on topographical factors can address the obstacles presented by dense vegetation and intricate terrain.

Future investigations should concentrate on experimental validation of these simulation outcomes, examination of temporal changes in connectivity, and expansion of the analysis to network-level performance metrics. Furthermore, exploring the potential of adaptive spreading factors and multi-gateway architectures could offer additional opportunities for enhancing LoRa networks in difficult forest settings.

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e-ISSN : 2541-2019
p-ISSN : 2541-044X

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