

Wireless Wave Attenuation in Forests: An Overview of Models

Yuewei Ma ^{1,2}, Wenbin Li ^{1,2,*}, Dongtao Han ^{2,3}, Yuan He ^{1,2}, Qingsong Li ^{1,2}, Xiaopeng Bai ^{1,2} 
and Daochun Xu ^{1,2} 

- ¹ School of Technology, Beijing Forestry University, No. 35 Tsinghua East Road, Haidian District, Beijing 100083, China; nanlinbeima1@bjfu.edu.cn (Y.M.); heyuan96@bjfu.edu.cn (Y.H.); lqs961012@163.com (Q.L.); xiaopengbai@bjfu.edu.cn (X.B.); xudaochun@bjfu.edu.cn (D.X.)
² Key Lab of State Forestry Administration on Forestry Equipment and Automation, Beijing Forestry University, Beijing 100083, China; hdt@hlbec.edu.cn
³ School of Technology, Hulunbuir College, No. 26 Chengjisihan Middle Road, Hulunbuir 021000, China
* Correspondence: leewb@bjfu.edu.cn

Abstract: In recent years, the need for reliable signal transmission in forested areas has increasingly grown, and the past few decades have witnessed significant developments in related research. With the emergence of smart forestry and precision forestry, understanding the science behind enhancing signal reliability in forests—specifically, studying the patterns and models of radio wave attenuation in these environments—has become crucial. To this end, we conducted a comprehensive review based on bibliometrics to summarize and construct the existing academic literature, revealing current research trends and hotspots. Utilizing bibliometric techniques, we analyzed the literature on radio wave attenuation in forests to summarize and evaluate previous studies. Our analysis indicates that empirical models (67%), hybrid models (21%), and equivalent models (12%) are the three main research clusters in this field. We observed that studies on radio attenuation are more prevalent in urban and artificial forests, while there is a scarcity of research in complex conditions like tropical rainforests and extreme weather; studies are more focused on UHF, VHF, and SHF frequency bands, with lesser attention given to other bands. Previous research has not adequately considered the impact of seasonal factors on signal attenuation patterns nor the influence of forest working environments.

Keywords: forest electromagnetic wave transmission characteristics; empirical models and formulas; forest conductivity and dielectric constant; meteorological impact



Citation: Ma, Y.; Li, W.; Han, D.; He, Y.; Li, Q.; Bai, X.; Xu, D. Wireless Wave Attenuation in Forests: An Overview of Models. *Forests* **2024**, *15*, 1587.
<https://doi.org/10.3390/f15091587>

Academic Editor: Giacomo Alessandro Gerosa

Received: 7 August 2024
Revised: 4 September 2024
Accepted: 7 September 2024
Published: 10 September 2024



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1. Introduction

As the widespread use of Multiple Input Multiple Output (MIMO) systems and Low-Power Wide-Area Networks (LPWANs) [1] continues to expand across various sectors, the deployment of high-penetration wireless communication networks in complex environments has diversified [2]. High-rate communication technologies often underperform in these challenging settings. Understanding the propagation patterns of electromagnetic waves and establishing environmental models are crucial for predicting and effectively designing reliable signal transmission systems tailored to complex environments. In today's era of advancing wireless communication technologies, a deep understanding of electromagnetic wave propagation in diverse settings is essential. Forested environments, in particular, are complex. Urban forests and gardens have become integrated into human living spaces [3]. In the United States, forest areas are divided into 19 sections, each with its own forest park system [4]; China has similar examples, like the Beijing Olympic Forest Park and Jiufeng National Forest Park. Urban forests, characterized by the high-density conditions of base stations, can utilize high-speed communication networks (4G, 5G, 6G, etc.). However, in areas with high canopy closure, the weak penetration of high-speed network signals remains a challenge for reliable electromagnetic wave transmission in forests. Additionally, in forests far from urban areas, jungles, and even tropical rainforests, ensuring reliable signal acquisition is a significant challenge in fields like forestry operations,

wilderness exploration, and military operations. Therefore, research on electromagnetic wave transmission in forest environments holds clear, practical significance.

Forests are dynamic media spaces where the transmission of electromagnetic waves at any given location exhibits anisotropic characteristics. Understanding the conductivity and permittivity of the medium space around LF (Low Frequency, 30 kHz to 300 kHz), MF (Medium Frequency, 300 kHz to 3 MHz), HF (High Frequency, 3 MHz to 30 MHz), VHF (Very High Frequency, 30 MHz to 300 MHz), UHF (Ultra High Frequency, 300 MHz to 3 GHz), and SHF (Super High Frequency, 3 GHz to 30 GHz) stations enables the simulation of ground power loss in the near-field (both vertically and horizontally) of high-frequency antennas. By considering the medium space's reflection, refraction, diffraction, and absorption, one can calculate the radiation pattern of the antenna. The International Telecommunication Union (ITU) has provided optimized standards for measuring these parameters in medium spaces. For the global conductivity map, please refer to Figure 41 in the ITU's P.832 recommendation, which shows the conductivity map of the People's Republic of China [5]. This figure, determined by the ITU, maps the medium-frequency ground conductivity in China. The map, broadly categorized by regions, provides conductivity ranges for specific areas. However, it does not accurately reflect the conductivity and permittivity of a specific forest medium space. Moreover, due to the anisotropic nature of forest environments, the electromagnetic radiation patterns in the near and far fields are significantly different, and there is a substantial difference between the vertical and horizontal radiation fields of antennas [6]. Therefore, analyzing the medium space in forests from the near-field to the transitional zone is particularly important.

In forests, the dielectric constant of elements such as leaves, branches, trunks, underbrush, stumps from felled trees, the ground, and the air within the medium space dynamically changes due to factors like seasonal variations, weather conditions, types of trees, and forest density. Simultaneously, the conductivity of these forests also varies dynamically. Serge Stroobandt [7] has described ground conductivity in different regions (see Table 1), which is particularly influential in the analysis of radio wave attenuation in forest environments where antennas are located close to the ground.

Table 1. Ground types used by L. B. Cebik, W4RNL.

Regional Description	Ground Quality	Conductivity σ (S/m)	Regional Description E_a
Urban, Industrial Areas	Very Poor	0.001	5
Sandy, Dry, Flat, Coastal Areas	Poor	0.002	10
Rocky Soil, Steep Hills, Typical Mountains	Poor	0.002	13
Pastoral, Mid-Hills, Plantations, Heavy Clay	Good	0.005	13
Pastoral Idyll, Low Hills, Fertile Soil	Very Good	0.0303	20
Saltwater	Very Good	5.0	81

Recently, significant advancements have been made in the application of Low-Power Wide-Area Networks (LPWANs) within forest environments, particularly in wireless sensor networks for scientific research and military operations [8], the use of drones for ground-to-air communication [9], and the fusion methods of information reliability transmission in forests using LiDAR [10,11]. Both analytical [12] and experimental [13] work has been completed. However, research in this field lacks a systematic approach and a comprehensive literature review necessary to understand its development trajectory. Scholars often abstractly perceive the forest environment, with limited knowledge of forestry operations and wood characteristics, treating the forest as a 'black box'. This approach simplifies the propagation model, facilitating the study of wave attenuation, but it has been overused, with recent years focusing more on signal attenuation in specific locations from an experimental data perspective, resulting in highly specific but less universally applicable results. This review aims not only to catalog the various models developed for predicting wireless wave attenuation in forests but also to critically assess their practical applicability,

strengths, and limitations. As a consequence, this work seeks to provide a comprehensive understanding that can guide future research and practical implementations in forestry operations and related fields. Blanchette [14] obtained data on wood density, fiber length, microfibril angle, and roughness through Terrestrial Laser Scanning (TLS). Just as electromagnetic waves diffract in the transmission through the “concrete jungle” in indoor and urban communication modes, studying wave transmission in forests from the perspective of forestry work and wood characteristics is crucial. This approach aligns with the direction of Forestry 4.0 in the context of Industry 4.0 [15], potentially advancing the informatization of forest management. The aim of this paper is to provide a comprehensive review of radio wave propagation in forests, focusing on predicting electromagnetic wave propagation loss by combining forest characteristics and forestry features. This review paper can serve as a reference for future large-scale research on radio wave propagation in forestry operations and as a guide for implementing modern wireless communication systems (such as MIMO and LPWAN) in forest environments. It reviews published results from 1960 to 2023.

2. Literature Review

The team led by Li Lewei, a fellow of the American Electromagnetics Academy and formerly of the Chinese Radio Wave Propagation Institute, has conducted extensive research in the physical modeling and mathematical derivation of wireless signal attenuation in forests. Since 1986, Li’s team has been collaborating with the Radio Wave Institute to study the laws and models of electromagnetic wave attenuation in forests and jungles [16,17]. Around the millennium, while serving as a professor at the National University of Singapore, Li remained active in publishing across various journals in this field [18–21]. His team has made significant foundational contributions to forest communication research. Li’s research is also based on Tamir’s four-layer forest medium model; hence, many recent studies still compare their findings with Tamir’s model to validate the reliability of their proposed methods.

Another notable contribution is a review written in 2009 by Yu Song’s team [22]. They conducted over five years of research at Nanyang Technological University on attenuation prediction in forest environments. This review covers the period from 1960 to 2009, focusing on the retrospective summary of experimental work performed in this field and the development of empirical propagation loss prediction models. The paper, covering most of the forest environment wireless transmission literature from 1963 to 2009, has been highly influential.

While these empirical models have played a significant role in the advancement of the field, it is important to acknowledge their inherent limitations. Empirical models, while widely used due to their simplicity and ease of application, often lack the precision required in highly variable forest environments. Their strength lies in providing quick, approximate predictions, but they may fall short in scenarios with complex terrain or variable foliage density. Conversely, equivalent models offer a more nuanced approach, considering multiple environmental factors, but they require extensive computational resources and detailed environmental data, limiting their practical use in large-scale applications.

Building on this foundational work and recognizing these challenges, this chapter primarily pays homage to the former, building upon the work of these pioneers. It aims to combine the knowledge of wood characteristics and forestry operations from Forestry Universities with further discussions on electromagnetic wave attenuation in forest environments. By integrating new technologies and methods with the foundational work of predecessors, this chapter summarizes the development trajectory of the field and rationally discusses future directions for forest communication.

3. Methods

This paper adopts a three-tiered progressive approach for literature selection, beginning with an initial screening of articles from academic databases such as Web of Science, IEEE, Springer, and Elsevier. Keywords like “forest communication”, “forest electromag-

netic waves”, and “jungle communication” were used to filter relevant articles. In the first step, a broad selection of literature was gathered, resulting in a total of 144 articles.

The second step involved a more detailed review and filtering of the literature. Initially, unrelated articles were removed based on the general direction of forest communication research outlined in this paper. The remaining articles from the initial set were then categorized into groups based on their relevance. Duplicate articles were identified and removed, further refining the selection. Finally, by closely examining the Title, Abstract, and Conclusion of each article, additional unrelated studies were eliminated. This thorough process resulted in a carefully curated set of 125 articles, ensuring that only the most pertinent studies were included for further analysis.

In the third step, a detailed reading was conducted, filtering out less relevant, low-quality articles M and adding additional policy and methodological references P. The final count of articles for the literature review was 95.

In addition to the standard selection criteria, special attention was given to studies that examined the impact of terrain and topography on wireless wave attenuation in forest environments. Variations in terrain, such as hills, valleys, and ridges, can significantly affect signal propagation by introducing additional factors like diffraction, reflection, and shadowing. Articles that addressed these elements were prioritized to ensure that the review comprehensively covers how these geographical features influence the effectiveness of communication systems in forests.

The research for this paper was organized using Research Rabbit, and a network of the main 81 articles was diagrammed, as shown below.

In phase 1, a series of questions were posed:

Q1: In current forestry practices, which specific electromagnetic wave attenuation and prediction models are frequently used to optimize communication systems in forests?

Q2: In the study of electromagnetic wave transmission in forests, which frequency bands are considered most critical, and how are these bands affected by canopy cover and terrain?

Q3: How are models of electromagnetic wave attenuation in forests adjusted or designed to ensure accurate prediction of signal attenuation under extreme weather conditions (such as storms or extreme temperature changes)?

Q4: How can models of electromagnetic wave attenuation in forests be integrated and applied in the future to enhance the stability and reliability of wireless communication systems in forestry operations?

Subsequently, the search strings were structured based on the compilation of the information presented in the review and overview articles. Figure 1 shows the number of relevant article hits categorized by key search terms like “Propagation”, “Forest”, and “Vegetation”.

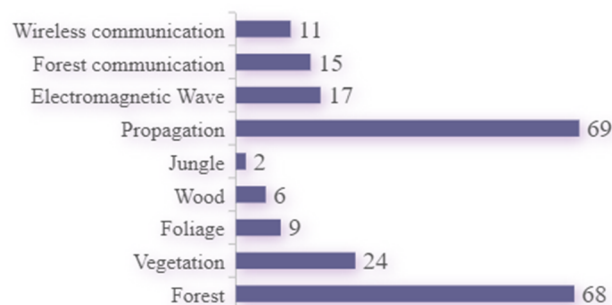


Figure 1. Number of relevant hits from article abstracts screened after retrieval, sorted by search terms.

4. Results

4.1. Descriptive Analysis

Further filtering by relevance, a total of 46 articles were selected for detailed study. Based on these articles, an additional 72 highly relevant papers were identified through

cross-referencing and expert recommendations. From a quantitative perspective, the literature search revealed the following insights:

- The term “Jungle” was mentioned only twice, indicating that it is not a commonly used keyword in current literature, and research on jungle-specific forest communication, prediction, and electromagnetic wave transmission is relatively scarce.
- “Propagation” and “Forest” are the most frequently occurring keywords, mentioned 69 and 68 times, respectively. This suggests that they are central concepts in the field of forest electromagnetic wave propagation. “Electromagnetic Wave” appeared 17 times and “Forest communication” 15 times, indicating their relative importance in the research, though not as primary focuses. By contrast, “Wireless communication” (eleven mentions), “Foliage” (nine mentions), and “Wood” (six mentions) are less frequently mentioned, possibly indicating a lower focus on these terms in forest electromagnetic wave propagation research.

There is a limited study on forest communication model frameworks, as per the summaries of the reviewed articles. It can be inferred that the research encompasses a range from empirical models (e.g., “Empirical Model” and “Forest radio Communication Attenuation and attenuation model”) to more theoretical and possibly simulation-based approaches (e.g., “DEM correcting” and “Wave Attenuation Model for Forest”). This progression reflects a trend from data-driven practical models to more complex, comprehensive models that might incorporate Digital Elevation Models (DEMs) and calculate wave attenuation in different forest layers. The adjacent pie chart (Figure 2) shows the proportion of studies classified into three types: empirical (67%), hybrid (21%), and equivalent (12%). This distribution suggests that a small portion of the research, labeled as equivalent, refers to the use of existing models or methodologies in new environments or adapting them to specific types of forests. Such studies seem to have plateaued around the year 2000, and the derivation of empirical formulas is inseparable from fundamental scientific research. The majority of the studies are empirical, possibly focusing on data and direct measurements observed in forest environments to develop models that can predict signal attenuation. A significant portion of the research is classified as hybrid, which may imply the development of new methodologies, application of new technologies, or introduction of original models in forest electromagnetic wave propagation research.

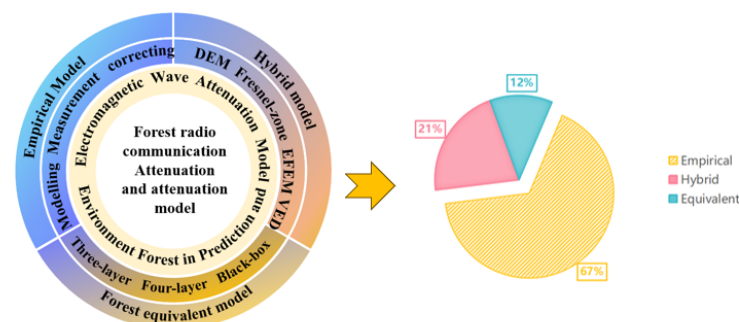


Figure 2. Framework diagram for forest communication.

4.2. Thematic Analysis

In forest environments, wireless wave attenuation is influenced by several critical factors, including tree density, foliage type, canopy structure, moisture content, and terrain variability. Dense forests with a high concentration of trees, especially those with thick foliage, lead to greater scattering and absorption of electromagnetic waves, increasing the overall attenuation. The type of vegetation also plays a significant role; for example, coniferous trees with needle-like leaves typically cause more scattering and higher attenuation compared to deciduous trees with broad leaves.

Path loss and shadowing are two distinct mechanisms that contribute to wireless wave attenuation. Path loss refers to the gradual reduction in signal strength as it propagates

through the forest, primarily due to the natural spreading of the wavefront (free-space loss), as well as the cumulative effects of scattering, diffraction, and absorption by trees, leaves, and other obstacles. This process is more pronounced in higher frequency bands, where shorter wavelengths are more susceptible to interaction with small-scale foliage elements. Shadowing, in contrast, is a more localized phenomenon where large objects, such as tree trunks, branches, or variations in terrain (e.g., hills or valleys), block or significantly diffract the signal, leading to areas of reduced signal strength or even complete signal loss. Shadowing results in more abrupt and location-specific attenuation compared to the more gradual path loss. This effect is particularly important for understanding the variability in signal strength across different locations within a forest, where line-of-sight (LoS) conditions are frequently interrupted using natural obstacles.

The combined effects of path loss and shadowing create a highly complex and variable environment for wireless signal propagation in forests, necessitating sophisticated modeling approaches that account for these factors to ensure reliable communication under such challenging conditions.

4.2.1. Forest Equivalent Model Research

This research primarily contributes to the foundational work in the field by deriving expressions for various waves in the process of electromagnetic wave transmission in forests. It considers the effects of both vertical and horizontal polarization of waves, deriving multidimensional expressions based on electromagnetic wave theory, which are then incorporated into attenuation models.

The origin and development of research on electromagnetic wave propagation attenuation in forests can be traced back to 1943. Influenced by jungle warfare, communication in forested areas became critically important. Herbstreit [23] analyzed the attenuation of VHF signals in the jungles of Panama and New Guinea during World War II based on data collected from tropical rainforests. Tamir [24] studied the propagation of medium to high frequency (1–100 MHz) electromagnetic waves in forest environments, specifically where both the transmitter and receiver are located within vegetation. He discovered that the radiation field of any directionally small dipole mainly consists of two separate waves and proposed a three-layer air-forest-ground propagation model for forests. Building on this, Dence [25] first proposed that forest electromagnetic wave loss can be divided into four levels. Inspired by Dence's theory, Cavalcante [26] and others developed a new four-layer medium forest model to more accurately calculate radio wave losses in forests. They divided the traditional forest layer into two lossy dielectric layers representing the canopy and trunks and conducted an in-depth analysis of the model using binary Green's functions. Figure 3 displays a standard four-layer medium forest model. In this model, several key factors affect signal transmission and attenuation: firstly, the height of the antenna [27–29]. Secondly, the density of the canopy significantly interferes with the propagation of low-frequency waves, causing multipath effects. Lastly, the undergrowth beneath the trunk layer affects the variation of H_2 , directly impacting the propagation of different wavebands. As shown in Figure 3, Li derived the electromagnetic wave reflection coefficients Γ for each layer using Green's function expansion method. These coefficients include the air-canopy layer Γ^{AC} , canopy-trunk layer $\Gamma_{\pm}^{CT}$, and trunk-ground layer $\Gamma_{\pm}^{TG}$.

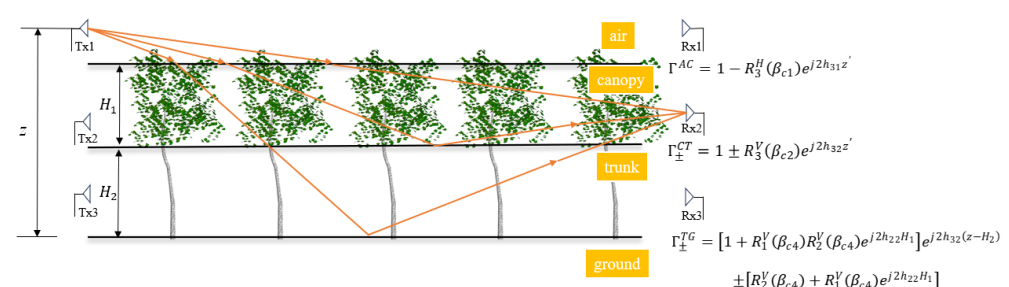


Figure 3. Classic four-layer medium space model.

Li Lewei from the Chinese Radio Wave Propagation Institute [16] expanded upon Cavalcante's four-layer jungle structure model. Utilizing the advantages of this model to explain the scattering effects of VHF frequency waves, Li employed the Dyadic Green's Function (DGF) method to solve for this new radiation field. Later, Li Lewei [17] published a paper in the *Journal of Communications*, delving deeper into mixed-path and multipath propagation modes in jungle communication. He combined the DGF method with the Steepest Descent Path (SDP) method and the Branch Cut Path (BCP) method to discuss the multipath propagation mode of the average field. Ultimately, he provided theoretical expressions for the propagation paths of direct waves, multiple reflected waves, and lateral waves along ground and air surfaces.

In subsequent work [18,19], Li Lewei based his study on this four-layer model to analyze the field, where the results primarily consisted of three wave modes: direct waves, multiple reflected waves, and lateral waves. By comparing these field components and calculating their dominant domains, he found that lateral waves play a major role in long-distance communication. Li also reanalyzed the propagation of non-uniform, isotropic RF waves along mixed paths in the 200–2000 MHz range within a four-layer medium [20]. He analyzed the closed-form, non-full-wave soft electric fields obtained in three areas (namely, the air, canopy, and ground layers). The dielectric constants of each layer also influence electromagnetic wave transmission, making such research often complex. Building on Tamir's research, Li Lewei defined the radio loss L from a tilted dipole to a vertically receiving antenna as

$$L(\text{dB}) = 36.57 + 20\log_{10} f + 20\log_{10}|E_0| - 20\log_{10}|E|.$$

In this formula, f is the frequency in GHz, E_0 is the field strength without a forest environment, and E is the total field strength resulting from the superposition of direct waves, multiple reflected waves, and lateral waves.

Building upon Li's research, Lijun et al. [30] provided a theoretical model for the propagation of vertically polarized radio waves in forests. This model considers different propagation paths, including directional and reflected waves at the air–forest interface and reflected and lateral waves along the air's upper interface at the forest–ground interface. Each layer of the medium needs to be considered for its unique characteristics.

In studies of single medium layers, researchers have shown interest in the effect of specific layers, such as the canopy layer and leaf characteristics, on electromagnetic wave diffraction. Foliage transmission loss refers to the attenuation of wireless signals as they pass through vegetation, particularly leaves, branches, and other forest elements. This loss is primarily due to the scattering and absorption of electromagnetic waves by the foliage. The impact of foliage transmission loss on wireless wave attenuation is frequency-dependent. Lower frequencies (e.g., VHF and UHF) tend to penetrate foliage more effectively, resulting in less attenuation, while higher frequencies (e.g., SHF and EHF) experience greater attenuation due to increased scattering and absorption by the smaller elements in the foliage. Understanding these effects is crucial for accurately predicting wireless wave behavior in different forest environments and for selecting the appropriate frequency bands for communication systems in such settings. For example, studies on leaf scattering in the canopy layer [9,31–38] gained traction in the early 21st century. Il-Suek Koh et al. [34] suggested that single scattering theory is insufficient for estimating the effective propagation constants in leaves at high microwave and millimeter wave frequencies. Broadleaf and coniferous clusters were treated as unit scatterers, and their collective forward scattering was used in the Foldy approximation to estimate leaf attenuation. Chee et al. [35] modeled leaves as thin lossy dielectric disks and petioles as thin lossy dielectric cylinders, verifying the model's reliability by comparing situations with and without leaves in winter and summer. Olufemi et al. [36] measured UHF broadcast signal strength in Nigeria during the rainy season (trees with leaves) and the dry season (trees with fewer leaves), considering leaf density as a model parameter. Meng et al. [32] compared and analyzed several renowned empirical leaf models in tropical plantations,

suggesting modifications to the ITU-R model considering lateral wave effects. The results aligned best with the FITU-R model developed by Al-Nuaimi and Stephens, which is an optimized model considering different path geometries, tree types, and forward scattering mechanisms at large leaf depths. Vougioukas et al. [37] studied radio propagation in a plum orchard at 2.4 GHz, finding that power attenuation was not severe at this frequency, mainly because the corresponding wavelength was larger than the average leaf size of plum trees. Thus, higher frequency signals with stronger penetration are more suitable for forest environments. Krraoui et al. [38] developed a new microwave method to simulate plant leaves in waveguides, measuring the relative complex permittivity of plant leaves in the 8–12 GHz range using a VNA HP8510C and rectangular waveguide method. Hampton [9] compared excess leaf attenuation and leaf depth measurements with various models, some of which had not appeared in the literature before, proposing a simple model to predict forest attenuation along low-elevation angled paths. Van Wesenbeeck [33] studied wave attenuation through forests under extreme conditions, observing that canopy surface area was most related to wave attenuation. Wu et al. [31] studied the impact of leaf area index on path loss in mixed forests at 433 MHz LoRa, considering antenna height. Wang et al. [39] developed a Statistical Wave Propagation Model (SWAP) to predict path loss in leaves, using a fractal-based Forest Coherent Scattering Model (FCSM) as the basis for predicting characteristics of wave interactions with leaves.

Forest Equivalent Bodies: Some researchers have studied the attenuation of electromagnetic waves in forests from the perspective of equivalent bodies, analyzing different equivalent conditions and filling mediums. Chen et al. [40] modeled the trunk layer as regular cylinders. N. Blaunstein et al. [41], while describing the propagation of radio waves in typical Danish forest terrains, also used cylindrical envelopes to represent trees. Atutov et al. [42] calculated the average field in a forest layer at any distance using multiple scattering methods and conditions of maximum filling mediums. This model represents a group of randomly distributed composite cylinders placed on the ground. Chee et al. [35] also used cylindrical envelopes to effectively represent specific tree characteristics while analyzing the impact of leaves. Picallo et al. [43] considered D2D (Device-to-Device) communications between components of Wireless Sensor Networks (WSNs) operating in vegetative environments, using rectangles and cones to represent broadleaf and coniferous trees, respectively. They proposed that the area away from trees, with an Obstructed Line of Sight (OLoS), fits the logarithmic distance model and examined the diffraction area around the edges of trees. Zabihi et al. [44] simplified the propagation model by equivalently modeling the tree canopy layer as cones, validating that the dual-mechanism model can accurately fit the double-slope profile for long-distance propagation through forests, a feat unachievable using the RET model. Sun et al. [45] used rectangular envelopes to represent the specific position of trees in a three-dimensional coordinate system while studying path loss models, proposing a novel environment-feature-based model for path loss prediction. However, this method failed to effectively express the multipath effects of signal transmission in dense forest environments, leading to significant errors under different environmental conditions; hence, its use stagnated in the early 21st century.

Equivalent models offer a more nuanced approach by considering multiple environmental factors. They provide more accurate attenuation predictions, especially in complex and variable forest environments. These models are useful for understanding the propagation characteristics of electromagnetic waves across different forest layers. Different types of trees, such as deciduous and coniferous species, have distinct effects on wireless wave attenuation in forests. Deciduous trees, which shed their leaves seasonally, typically cause less attenuation during leaf-off periods compared to coniferous trees, which maintain dense foliage year-round. The needle-like leaves of coniferous trees are particularly effective at scattering electromagnetic waves, leading to higher levels of attenuation, especially at higher frequencies. In contrast, broadleaf deciduous trees, while also causing attenuation, generally allow for more signal penetration due to their less dense canopy. Tree density further exacerbates wireless wave attenuation. In dense forests, the probability of a signal

interacting with obstacles increases, leading to more significant scattering and absorption. This higher density not only increases overall path loss but also contributes to multiple scattering effects. Multiple scattering occurs when a signal is scattered multiple times by leaves, branches, and trunks, resulting in a complex propagation environment that can greatly reduce signal strength by the time it reaches the receiver. The concept of multiple scattering is particularly relevant in forests with high tree density, where the cumulative effect of these interactions leads to greater attenuation than predicted by simpler models that consider only single scattering events. Understanding and modeling these effects are crucial for accurately predicting wireless wave behavior in dense forest environments. However, despite their accuracy, equivalent models require extensive computational resources and detailed environmental data, which limits their practical use in large-scale applications. The complexity of these models also poses challenges for practical implementation.

In recent years, foundational scientific research in this field has been somewhat lacking. Technological methods from the last century have undergone significant changes compared to this century's technologies. Current technological means, such as LiDAR scanning and point cloud techniques, can achieve three-dimensional modeling of forest environments. This opens up possibilities for research on forest electromagnetic wave attenuation models based on three-dimensional forest models, offering a more comprehensive perspective than previous approaches.

4.2.2. Empirical Formulas and Models

The Application History of Empirical Models in Forest Electromagnetic Wave Attenuation Research: Empirical models and formulas, due to their convenience and high specificity, have been interwoven into the research of forest electromagnetic wave attenuation [9,27,29,40,41,46–54]. They have become one of the mainstream research methods in this field. Most of these studies are based on the MED model from the preliminary important summary of models for predicting radio wave attenuation through trees by Weissberger [47] of the United States Department of Defense Electromagnetic Compatibility Analysis Center, and attenuation models such as ITU-R P.833 [55], ITU-R [56], COST235, and FITU-R [57] proposed by the International Telecommunication Union (ITU) [29]. These are compared with the empirical formulas presented in this paper. Table 2 shows the research on empirical formulas around the 21st century. Chen et al. [40] established an empirical formula after extensively calculating the radio loss of the optimal four-layer forest model using the least squares curve fitting method. This empirical formula is applicable for calculating radio loss in forest environments within the 1–100 GHz frequency range. N. Blaunstein et al. [41] considered an empirical short-range path loss model based on measurements conducted in typical Danish forest areas.

The formulas presented in Table 2 include various parameters essential for predicting electromagnetic wave attenuation in forest environments. For instance, frequency (f) and distance (d) are fundamental variables used across multiple models, such as the Weissberger and ITU-R models, where L_W (dB) and L_{ITU-R} (dB) represent the path loss in decibels. The parameter d_{fd} , which denotes the distance within the forest, is specifically tailored to account for the particular environmental conditions of the forest, allowing for more precise predictions over specific distances. In the Tewari model, additional parameters like A_2 (attenuation constant) and α_2 (attenuation factor) further refine the accuracy of path loss predictions by considering the effects of foliage density and other forest characteristics.

Other models, such as COST235 and FITU-R, introduce complex parameters to account for varying environmental conditions. For example, the COST235 model's formula includes frequency (f) and distance (d_f), with different values depending on whether the trees are in or out of leaf, thus adapting the model to seasonal changes. Similarly, the Goldman and Blaunstein models incorporate parameters like reflection coefficients and wave impedance to address the complex interactions between electromagnetic waves and the forest environment. In more advanced models like those by Kovacs and Chen, parameters such as L_f , L_0 , L_{ant} , and L_{veg} are used to describe the total path loss, initial path loss, antenna-related

loss, and vegetation-induced loss, respectively. These models also account for polarization effects, using L_{V-V} (dB) for vertical polarization and L_{H-H} (dB) for horizontal polarization, providing a more comprehensive understanding of wave behavior in diverse forest terrains. Finally, Blaunstein's model uses advanced parameters like wavelength (λ) and attenuation factors (γ_0, Γ) to calculate total path loss in more complex environments, considering factors related to terrain and wave interactions.

Table 2. Research on empirical formulas before and after the 21st Century.

Model	Empirical Formula	Frequency Band	Data
M. A. Weissberger [47]	$L_W(\text{dB}) = \begin{cases} 1.33 \times f^{0.284} d_f^{0.588} & 14 \text{ m} < d_f \leq 400 \text{ m} \\ 0.45 \times f^{0.284} d_f & 0 \text{ m} \leq d_f < 14 \text{ m} \end{cases}$	LF MF HF VHF UHF	1982
ITU-R [50]	$L_{ITU-R}(\text{dB}) = 0.2 \times f^{0.3} d_f^{0.6}$	VHF UHF SHF	1986
R. K. Tewari [46]	$L_{Tewari} = -27.57 + 20\log_{10}(f) - 20\log_{10}\left(\frac{A_2 \exp(-\alpha_2 d)}{d} + \frac{B_2}{d^2}\right) [\text{dB}]$	UHF	1990
COST235 [58]	$L_{COST}(\text{dB}) = \begin{cases} 26.6 \times f^{-0.2} d_f^{0.5} & \text{out-of-leaf;} \\ 15.6 \times f^{-0.009} d_f^{0.26} & \text{in-leaf.} \end{cases}$	VHF UHF SHF	1995
FITU-R [59]	$L_{FITU}(\text{dB}) = \begin{cases} 0.39 f^{0.39} d^{0.25} & \text{in-leaf} \\ 0.37 f^{0.18} d^{0.59} d^{0.59} & \text{out-of-leaf} \end{cases}$	VHF UHF SHF	1998
J. Goldman [48]	$L(\text{dB}) = a + b[\log(d)]$	VHF UHF	1999
Z. Kovacs [49]	$L_f = L_0 + L_{ant} + L_{veg} [\text{dB}]$	VHF UHF	1999
H. Chen [40]	$L_{V-V}(\text{dB}) = (0.001 \times f + 0.2) \times d + (0.5 \times f + 3)$ $L_{H-H}(\text{dB}) = (0.0002 \times f + 0.2) \times d + (0.03 \times f + 2)$	UHF	2001
N. Blaunstein [41]	$L_{total} = 10\log \left[\lambda^2 \left(\frac{1}{(4\pi)^2} \frac{\exp(-\gamma_0 \rho)}{\rho^2} \left[2\sin \frac{kz_1 z_2}{\rho} \right]^2 + \frac{\gamma_0 \Gamma}{(4\pi)^2} \left[\frac{\Gamma^3}{4(8)^3} \frac{\exp(-\gamma_0 \rho)}{\rho} + \frac{\Gamma}{32} \left(\frac{\pi}{2\gamma_0} \right)^{1/2} \cdot \frac{\exp(-\gamma_0 \rho)}{\rho^{3/2}} + \frac{\exp(-\gamma_0 \rho)}{2\gamma_0 \rho^2} \right] \right) \right]$	VHF UHF	2003

These empirical models are vital as they provide practical and efficient means for predicting electromagnetic wave attenuation in forest environments. They are particularly useful when detailed physical modeling is either impractical or when rapid assessments are needed. Despite their limitations in capturing the complexity of forest environments, empirical models have proven to be indispensable tools in the field of forest electromagnetic wave studies.

Research Progress of Empirical Models and Formulas Before and After the 21st Century: Empirical models and formulas have played a significant role in the study of forest electromagnetic wave attenuation due to their practicality and specialization. These studies are often based on Weissberger's MED model and various ITU models, validating predictions by inputting experimental data.

Meng et al. [50] conducted path loss modeling by integrating the effects caused by leaves and radio wave reflections, finding that in tropical forests, the VHF band COST235 model and the ITU-R model best fit the two forest propagation channels considered. Bitirgan et al. [51] developed empirical models for GSM 900, GSM 1800, and CDMA 2100, which can be easily obtained for specific environments using environmental measurements and open-area measurements. The model error increased from 900 MHz to 1800 MHz but decreased for CDMA2100. Anderson et al. [52] used UWB pulses with a frequency range of 830–4200 MHz and a duration of 620 ps for path loss measurements. Small-scale fading analysis showed that UWB signals experienced Ricean fading with a K factor in the range of 10–16 dB, concluding that UWB propagation in forests largely depends on forest density, antenna type, and forest configuration. Azevedo et al. [53] developed a model using tree density, average canopy diameter, and leaf density as input parameters. Comparisons with famous empirical models showed lower error introduction in attenuation estimates when using the new model. Ibdah et al. [54] conducted IV2IV and IV2W channel measurements,

capturing the effects of mobile stations mounted inside vehicles in forests and urban areas at 2.1 GHz.

Oestges et al. [56] characterized directional propagation channels in forest areas at 1.9 GHz with medium antenna heights, finding that ITU-R Recommendation 833-4 well-simulated path loss. They also analyzed time fading and multipath dispersion, with delay spreads in the 60 to 120 ns range strongly inversely correlating with temporal coherence (measured by the Ricean K factor) and increasing with the distance from transmission to reception. Azevedo et al. [60] proposed a model aiming to estimate the main parameters of a log-normal model suitable for measured data, with propagation paths primarily characterized by trunks. They found signal attenuation depended on vegetation density, which they defined as the product of tree density and average trunk diameter. Zhang et al. [30] measured short-range, temperate, medium-density forest wireless channel characteristics under a signal with a center frequency of 5.12 GHz and a bandwidth of 50 MHz. Gay-Fernandez et al. [61] conducted measurements in two different grassland scenarios and four forest types, collecting over two million received power samples to obtain the main propagation parameters for each environment studied. The average error was in the same order of magnitude as that provided by ITU-R Recommendation P.833, which is intended for wireless links from base stations to mobile terminals in LTE. Ghoraishi et al. [62] studied radio channels in dense vegetation, identifying three major classes of received multipath associated with individual final scattering leaves by observing received radio signals measured in the angular domain with high resolution. Ferreira et al. [63] studied LoRa signal propagation in forest, urban, and suburban vehicular environments. In forest scenarios, the link reached up to 250 m, while in vehicular scenarios, it reached up to 2 km. By contrast, in high-density buildings and human activity scenarios, the maximum range in urban scenarios is up to 200 m. De Beelde et al. [64] presented vegetation loss measurements for different types of vegetation, including trees, hedges, and forests, in the 110 to 170 GHz frequency range. They proposed an experimental method to determine the average loss per meter of vegetation depth (VD) for different types of vegetation.

Innovation Developments in Forest Electromagnetic Wave Path Loss Prediction Models: Xu et al. [65] proposed a generalized radio wave propagation loss prediction model, introducing a theoretical study for calculating path loss fields in forest environments. The results involved relatively simple formulas that could be explained using ray paths. Azevedo et al. [66] estimated path loss indices for different antenna directivities, given a known path loss index for a reference antenna. They developed a model that links antenna gain and beamwidth to the parameters of the log-normal model, enabling a more nuanced understanding of how different antenna characteristics influence path loss in forested areas. Barrios-Ulloa et al. [67] conducted a Systematic Literature Review (SLR) aimed at identifying widely used propagation models in the deployment of Wireless Sensor Networks (WSNs) in agricultural or natural vegetative environments. Their goal was to assess the effectiveness of these models in estimating signal loss, which is crucial for optimizing WSN performance in such environments. Hakim et al. [68] presented and analyzed a LoRa path loss propagation model specifically for near-ground propagation or situations where the transmitter and receiver antennas are at a low height above the ground (antenna height less than 30 cm). This study is significant for understanding signal behavior in scenarios where typical propagation models might not be accurate due to the low height of antennas.

Equivalent models also play a critical role in advancing our understanding of electromagnetic wave propagation in forests. These models offer a more nuanced approach by considering multiple environmental factors, allowing for more accurate attenuation predictions, especially in complex and variable forest environments. They are particularly useful for understanding the propagation characteristics of electromagnetic waves across different forest layers. However, despite their accuracy, equivalent models require extensive computational resources and detailed environmental data, which limits their practical use in large-scale applications. The complexity of these models also poses challenges in practical implementation.

These innovative approaches reflect the ongoing evolution in modeling and predicting electromagnetic wave propagation in forest environments, addressing various complex factors such as antenna characteristics, vegetative cover, and specific deployment scenarios. Such advancements are critical for enhancing the accuracy and reliability of wireless communications in forested and natural areas.

The formulas in Table 3 include various empirical models for predicting electromagnetic wave attenuation in forest environments. Each formula uses specific parameters that are essential for accurate path loss calculations. For instance, in the Meng model, $PL_{\text{forest}}(d)$ represents the path loss as a function of distance d , with B and C being additional attenuation factors that adjust the model based on specific forest conditions. In the Oestges model, the average path loss $\bar{P}(d)$ is calculated using an integral that accounts for time delay τ , frequency f , and other factors influencing signal strength over a given distance d . The ITU model simplifies this by focusing on frequency f and distance d as the primary variables affecting the path loss L_{ITU} .

Table 3. Recent developments in empirical formulas.

Model	Empirical Formula	Frequency Band	Date
Meng [22]	$PL_{\text{forest}}(d) = 10A\log_{10}(d) + Bd + C(\text{dB})$	VHF UHF	2009
C. Oestges [56]	$\bar{P}(d) = \frac{1}{N} \sum_{n=1}^N \frac{1}{2T} \int \left \int h(t, \tau, n, d) d\tau \right ^2 dt$ $= \bar{P}_n(d)$	UHF	2009
LITU [32]	$L_{\text{LITU}}(\text{dB}) = 0.48f^{0.43}d^{0.13}$	VHF	2009
M. Bitirgan+Friis [51]	$PL(\text{dB}) = 10\log(G_t G_r) + 20\log\lambda - 20\log(4\pi d) - 10\log L$	UHF	2011
J. A. R. Azevedo [60]	$PL(d_0) = (-0.026d_m + 0.49f^{0.47})TD * D + 20\log_{10}\left(\frac{c}{4\pi f}\right)$	UHF	2011
C. R. Anderson [52]	$PL_{\text{measured}}(d) = PL(d) - PL(d_0) = -10\log\left(\frac{\sum_r v_r^2 \Delta\tau_r}{\sum_r v_{cal}^2 \Delta\tau_{cal}}\right)$	UHF SHF	2013
J. A. Azevedo [66]	$PL(\text{dB}) = PL(d_0)_{\text{ref}} + 10(n_{\text{ref}} + n_A)\log_{10}\left(\frac{d}{d_0}\right)$	UHF	2015
J. A. Azevedo [53]	$\tilde{P}\tilde{L}(d_0) = PL(d_0)_{\text{FS}} + \Delta P\tilde{L}(d_0)$ $= PL(d_0)_{\text{FS}} + m_1 \times FD + m_2$ $\cong PL(d_0)_{\text{FS}} + m \times (FD - 15) + 1,$	SHF UHF	2016
ITU-R P.833-9 [55]	$L_{ex} = 0.25f^{0.39}d_f^{0.25}\theta^{0.05}$	VHF UHF SHF	2016
ITU-RP.833-9 MA [55]	$L_{MA} = A_m \left[1 - \exp\left(-\frac{D_{\text{E}}}{A_m}\right) \right] [\text{dB}]$	VHF UHF SHF	2016
NZG [55]	$L_{\text{NZG}} = R_{\infty}d + k \left[1 - \exp\left(-\frac{(R_0 - R_{\infty})}{k}D\right) \right]$	VHF UHF SHF	2016
Y. Ibdah [54]	$PL(d) = PL(d_0) + 10n\log(d/d_0)$	UHF	2017
J. Hejselbaek [29]	$L_{\text{stat}} = -10\log_{10}[\exp(-\theta_0 D) \times \left(\frac{\Theta}{2} + 4\sin^2\left(\frac{2\pi h_{tx}h_{rx}}{\lambda D}\right)\right)]$	UHF	2018
J. R. Hampton [9]	$L_{ex} = P_t + G_t - P_r + G_r - L_{fs}$	UHF	2019
B. Myagmardulam [27]	$L_{fspl}(\text{db}) = 20\log_{10}(4\pi d/\lambda)$	UHF	2021
ITU-R P.2108 [69]	$L_C = -5\log(10^{-0.2L_l} + 10^{-0.2L_s})[\text{dB}]$ $L_l = 23.5 + 9.6\log(f)[\text{dB}]$ $L_s = 32.98 + 23.9\log(D) + 3\log(f)[\text{dB}]$	VHF UHF SHF	2021
ITU-R P.833-10 [70]	$L_{ex} = 0.25f^{0.39}d_f^{0.25}\theta^{0.05}$	VHF UHF SHF	2021

Other models in the table introduce more complex parameters to account for various environmental and technical factors. For example, in the M. Bitirgan model, the path loss $PL(d_0)$ is influenced by the transmitter and receiver gains G_t and G_r , the wavelength λ , and the distance d , among other factors. The Anderson model further refines this by considering the variance in time delay $\Delta\tau$ and the velocity v of the signal in the environment, leading to a more precise calculation of the measured path loss $PL_{\text{measured}}(d)$. Additionally,

parameters such as L_{MA} and L_{NZG} in other models reflect specific attenuation due to factors like canopy density D , tree height, and ground conditions, which are critical in diverse forest terrains. These detailed variables help improve the accuracy of path loss predictions across different types of forests and environmental conditions.

In recent years, significant advancements have been made in the field of forest electromagnetic wave attenuation through empirical models and formulas. Researchers have improved prediction accuracy by comparing and refining Weissberger's MED model, various ITU models, and new empirical formulas, developing models suitable for different frequencies and forest types. Studies have ranged from the propagation of high-frequency UWB signals in forest environments to explorations of empirical models for GSM and CDMA signals in specific environments and to research on the propagation characteristics of LoRa technology in complex settings. Each of these efforts has deepened our understanding of radio wave propagation behaviors in forests. These studies are not only crucial for guiding the development of wireless communication technologies but also for providing technical support for monitoring electromagnetic environments in forests. The insights gained from these research endeavors help optimize wireless network deployment in forested areas, improve communication reliability for forestry operations, and enhance the effectiveness of environmental monitoring systems in such challenging terrains.

4.2.3. Hybrid Formulas and Models

Recent contribution in this field mainly lies in the research on the attenuation patterns of electromagnetic waves in forests, utilizing equivalent models, empirical formulas, and a combination of mathematical methods or advanced technologies.

Zhang et al. [71] proposed a model based on forest surface characteristics, consisting of Fractional Brownian Motion (FBM) and band-limited Weierstrass Function (BWF), suitable for evaluating electromagnetic wave scattering on forest surfaces using Kirchhoff approximation and small perturbation theory. Meng et al. [72] conducted studies on the dynamic characteristics of tropical forest channels affecting the propagation of Very High Frequency (VHF) and Ultra High Frequency (UHF) radio waves based on the principles of the Fresnel zone. T.N. Chymitdorzhiev et al. [73] introduced a theoretical model for assessing the wave field amplitude of forest electromagnetic wave attenuation based on the Kirchhoff–Fresnel principle, where the E_y or H_y components of the wave field at the receiving point can be represented in the form of a surface integral. Torabi et al. [74] developed a computationally efficient near-field prediction model to facilitate realistic simulations of Wireless Sensor Networks (WSNs). In this model, path loss is divided into three sections using the principles of the Fresnel zone.

Satellite remote sensing and LiDAR have increasingly been used to optimize the prediction of the Path Loss Exponent (PLE). Jiang et al. [75] reported preliminary results of a new method for predicting the PLE value through satellite remote sensing observations. Lei et al. [76] demonstrated that Kullback–Leibler distance (KLD), log-logistic, G_0 , and G distributions with estimated parameters are the best choices for modeling clutter in Line-Of-Sight (LoS) forest environments, Non-Line-Of-Sight (NLOS) forest penetration environments, and NLOS shrubbery. Jawhly et al. [77] proposed a new forest cover classification defined by Line of Sight (LoS). Ray tracing has also become a method for obtaining electromagnetic behavior. Leonor et al. [78] developed a novel two-dimensional model to characterize the electromagnetic behavior of trees for ray-tracing-based simulation platforms. Silva et al. [79] described the use of an asymptotic method (ray tracing) for simulating the propagation of Ultra-Wideband (UWB) radio signals in urban channels with dense trees.

The Parabolic Equation method (PE) [80–86] has also been used to model electromagnetic wave propagation in forests. This method simplifies the system into a tridiagonal system, solved using the Crank–Nicolson type implicit finite difference format. It is an unconditionally stable method that allows for intermediate parameter changes without losing stability. Fourier Transform (FT) and Split-Step Fourier Transform (SSFT) are used

to calculate and predict forest electromagnetic wave propagation loss. However, due to the accuracy of the parabolic method and the computational complexity of Fourier transforms, this method has not seen many high-level journal publications, and research often remains superficial.

This section of research demonstrates a variety of methods and models used to explore and understand the propagation and attenuation of electromagnetic waves in forests. These approaches include models based on forest surface characteristics, theoretical models, and advanced technological methods like ray tracing and satellite remote sensing. Researchers have utilized classical theories such as the Kirchhoff approximation, Fresnel zone principles, and the Parabolic Equation method, but they have also integrated modern technological means like LiDAR and ray tracing, showcasing an effective combination of traditional methods with modern technology.

Shehadeh et al. [87] considered three multi-objective algorithms—NSGA-II, SPEA-II, and OMOPSO—to find optimal values in network topology planning to mitigate the issue. Zabihi et al. [44] discussed two parallel transmission mechanisms: direct transmission through a series of trees modeled by simple linear transmission lines and transmission over the top of the forest modeled using simplified multiple-edge diffraction. They proved that this dual-mechanism model can accurately fit the double-slope profile for long-distance propagation through forests, a feat unachievable via the RET model. Costa et al. [88] assessed the performance of models based on the Uniform Theory of Diffraction (UTD) for predicting RF path loss in such ridges. Sun et al. [45] noted that traditional statistical path loss models are based on high-dimensional data without utilizing specific environmental features. They proposed a novel Environment-Feature-Based Model (EFBM) for path loss prediction.

The strengths of these hybrid models lie in their ability to utilize advanced technologies such as LiDAR, ray tracing, and satellite remote sensing to significantly improve the accuracy of electromagnetic wave attenuation predictions in forests. These models can capture complex environmental features and dynamics, leading to more precise predictions under various conditions. Additionally, the integration of modern algorithms and computational methods, like the Parabolic Equation method and Fourier Transforms, allows for the simulation of complex scenarios that were previously difficult to model accurately. This provides a more detailed understanding of specific propagation phenomena, such as the interaction between electromagnetic waves and different types of forest vegetation.

However, despite these advanced capabilities, these hybrid models often come with increased computational complexity and resource demands. The need for detailed environmental data and sophisticated computational infrastructure can limit their practical application, especially in large-scale or real-time scenarios. Moreover, while these models excel in specific, controlled environments, they may still face challenges in generalizing their results across different forest types or under varying conditions. The high level of detail required for accurate predictions can also lead to difficulties in model implementation and validation, potentially limiting their broader adoption.

These studies are not limited to theoretical models but also discuss specific application scenarios, such as simulations of Wireless Sensor Networks (WSNs), propagation of Ultra-Wideband (UWB) radio signals in urban channels, and the characteristics of radio wave propagation in different forest types, including tropical forests. Although existing research has yielded rich results, the propagation of electromagnetic waves in forests remains a complex and variable field, requiring more in-depth research to understand and predict the impacts of various environmental factors on electromagnetic wave propagation. Particularly, integrating more modern technologies and advanced algorithms is expected to yield more precise and practical prediction models in future research.

5. Discussion

5.1. Model Characteristics and Practical Applications

When comparing the results of different models, it is evident that each type offers distinct advantages and challenges, depending on the specific application and environmental context. The choice of model should be guided by the complexity of the forest environment, the desired accuracy, and the available computational resources.

Empirical models are primarily derived from extensive experimental data collected in various forest environments. These models are designed to be simple and easy to use, making them effective for quick and straightforward predictions. They work particularly well in more uniform forest settings, where environmental factors do not vary significantly. The simplicity of empirical models allows for rapid deployment and minimal computational demands, which is advantageous in real-time applications. Empirical models have been widely applied in basic forestry operations, such as communication network planning in suburban forests, tree farms, and other managed environments. They are especially useful in scenarios where the environment is relatively stable, and the need for immediate results outweighs the need for high precision. For instance, empirical models have been used to predict signal loss in environments with consistent canopy cover and minimal terrain variation. The main strength of empirical models lies in their ability to deliver quick and practical results with low computational costs. However, their oversimplification of forest environments can lead to significant inaccuracies when applied to more complex or dynamic settings. Future research could aim to refine these models to enhance their accuracy in diverse environments while maintaining their practical advantages.

Equivalent models represent a more sophisticated approach to predicting electromagnetic wave attenuation in forests. These models incorporate multiple environmental factors, such as canopy density, terrain variability, and vegetation types, allowing for more accurate and nuanced predictions. The detailed consideration of these factors makes equivalent models particularly suited for complex forest environments where precision is crucial. Equivalent models are especially useful in specialized forestry operations that demand high accuracy. They have been applied in the deployment of Wireless Sensor Networks (WSNs) in dense or mountainous forests, where understanding wave attenuation is critical for maintaining effective communication. These models are also valuable in research settings, where they help explore the detailed interactions between electromagnetic waves and forest environments, providing insights into propagation characteristics across different forest layers. The enhanced accuracy of equivalent models comes at the cost of increased computational demands and the need for detailed environmental data. These requirements can limit their practical application in large-scale or real-time scenarios. Therefore, future research should explore hybrid models that combine the precision of equivalent models with the simplicity and efficiency of empirical approaches, thus expanding their utility in a wider range of forestry applications.

Hybrid models utilize cutting-edge technologies, such as LiDAR, ray tracing, and satellite remote sensing, to achieve high precision in predicting electromagnetic wave attenuation. These models integrate modern computational techniques like the Parabolic Equation method and Fourier Transforms, enabling the simulation of complex scenarios that traditional methods cannot easily handle. Hybrid models are at the forefront of forest communication research, offering detailed insights into the interactions between electromagnetic waves and diverse forest environments. The application of hybrid models is particularly relevant in advanced forestry operations and research initiatives that require the highest levels of accuracy. These models have been employed to optimize communication strategies in challenging environments, such as tropical rainforests and mountainous areas, where traditional models fall short. They are also essential in the development of new communication technologies and in planning forestry operations that involve complex environmental factors. While hybrid models provide unmatched accuracy, their complexity and high resource requirements can limit their practical application, especially in real-time or large-scale forestry operations. Nonetheless, their ability to account for the full complex-

ity of forest environments makes them invaluable in settings where precision is critical. Future research should focus on reducing the computational demands of these models, making them more accessible for practical use while retaining their high accuracy.

To mitigate the effects of wireless wave attenuation in forests, several techniques and models are commonly used. Directional antennas and beamforming are effective methods that focus the signal in specific directions, reducing the impact of scattering and absorption. Adaptive modulation and coding (AMC) dynamically adjust transmission parameters based on real-time channel conditions, maintaining reliable communication even in challenging environments. MIMO systems improve signal robustness by leveraging multiple antennas, which is particularly beneficial in dense forests with high multipath propagation.

In terms of predictive models, empirical models like the ITU-R and Weissberger's models are widely used for their simplicity in less complex environments. For more challenging forest environments, equivalent models such as the FITU-R model offer better accuracy by considering factors like tree density and terrain variations. Hybrid models, which integrate empirical, equivalent, and computational techniques, including ray tracing and LiDAR-based models, provide the highest precision for advanced applications, particularly when detailed environmental data are available. These models and techniques are critical for developing robust and reliable wireless communication systems in forest environments.

Each model type—empirical, equivalent, and hybrid—has its strengths and weaknesses, making them suitable for different forestry applications. Empirical models offer simplicity and speed, equivalent models provide detailed accuracy, and hybrid models push the boundaries of what is possible with modern technology. By understanding these characteristics, researchers and practitioners can choose the most appropriate model for their specific needs. The future of forest communication systems may involve hybrid models that integrate the benefits of all three approaches, providing a balanced solution that meets both practical and research-oriented demands.

5.2. Complex and Adverse Forest Environments

The field of forest communication has developed a wealth of empirical models through extensive experimental research conducted globally. These studies have involved on-site experiments in various forest environments, including jungles, suburban forests, and tree farms. However, despite the breadth of research, only about 10% of the articles specifically focus on these environments, which are often characterized by their unique and challenging conditions for electromagnetic wave propagation.

Table 4 provides a comprehensive summary of findings from various studies that have measured and reported the loss or attenuation of electromagnetic waves in these diverse forest environments. The table serves as a valuable reference, highlighting the range of expected losses across different conditions and helping to identify the most challenging environments for signal transmission. This detailed comparison allows researchers to better understand the variability in wave behavior across different forest types. Such insights are crucial for refining existing models and developing new strategies that can effectively address the specific challenges posed by these complex environments. Furthermore, this understanding is vital for optimizing wireless communication systems, ensuring that they perform reliably even in the most demanding forested areas. By leveraging the information in this table, future research can focus on bridging the gaps in current models, leading to more accurate and robust predictions for a wide range of forest environments.

Table 4 discusses the challenges associated with using standard formulas set by the International Telecommunication Union (ITU) for complex forest environments. These standard formulas often exhibit significant errors when applied to complex forest medium spaces, as they do not adequately adapt to the specific conditions of signal transmission in forests. Figure 4 primarily serves to showcase the characteristics of complex forest environments under varying conditions. The images in the figure illustrate how different seasonal and weather conditions, as well as terrain types, can drastically alter the forest medium space, thereby affecting electromagnetic wave propagation. Panels Figure 4a–d

depict the transitions in forest environments across the seasons—spring, summer, autumn, and winter—each bringing unique challenges to signal transmission due to changes in foliage density, moisture levels, and overall vegetation structure. Panel Figure 4e highlights the impact of rugged, mountainous terrain on signal behavior, where elevation and ground irregularities introduce additional complications. Panel Figure 4f presents a dense tropical rainforest, where high humidity and thick vegetation create a challenging environment for wave propagation. Lastly, panels Figure 4g–i demonstrate the effects of extreme weather conditions, including heavy rain, snow, and strong winds, which can further disrupt signal paths by dynamically altering the forest structure and medium.

Table 4. Research on electromagnetic waves in complex forest environments.

Name	Frequency Range	Terrain	Citations	Reported Loss/Attenuation
Herbstreit	VHF	Jungle	[23]	Up to 100 dB, especially in areas with dense jungle vegetation
Weissberger	Various	Jungle	[47]	Loss values ranging from 10–60 dB, depending on frequency and forest density
Tewari	VHF	Jungle	[46]	60–70 dB in dense rainforest conditions, with significant variations based on foliage density
Gans	VHF/UHF	Mountain forest	[89]	30–50 dB, with higher losses in more rugged terrains
Meng	40 MHz to 1400 MHz	Jungle	[90]	100–120 dB for different frequencies, with higher losses at higher frequencies
Phaiboon	1.8 GHz	Suburban forest	[91]	50–60 dB with higher losses in denser tree environments
Meng	Near-ground, 40 MHz to 2.4 GHz	rainforest	[32]	50–80 dB, with lower frequencies showing better penetration
Olufemi	UHF Band	Jungle	[36]	Up to 20 dB higher loss in the wet season compared to the dry season
Ibdah	VHF/UHF	Suburban forest	[54]	Losses around 30–40 dB for low-height antennas in denser forests
Dias	25, 60, 81 MHz	rainforest	[92]	50–120 dB depending on frequency; mean error: ≤ 3.0 dB. Standard deviation: ≤ 4.3 dB
Pal	2.4 GHz	Farm	[93]	40–50 dB depending on tree density and foliage conditions
Zhang	200 to 2600 (MHz)	Suburban forest	[94]	Shadow fading std dev: 4.8–10.1 dB

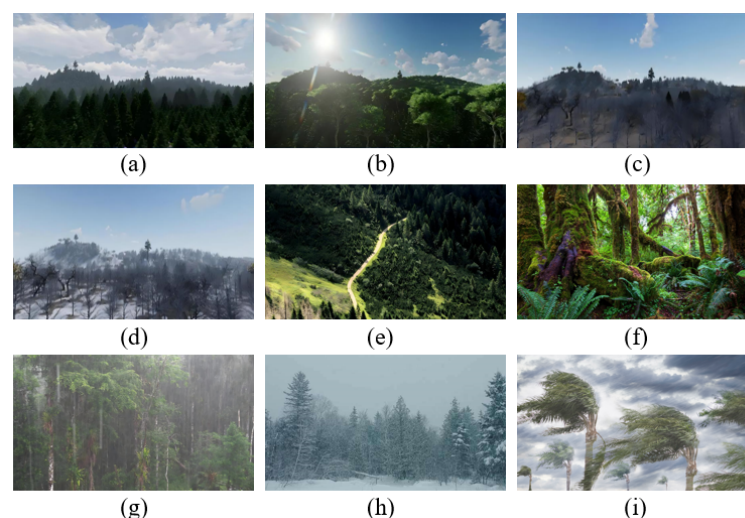


Figure 4. Changes in forest electromagnetic wave medium spaces.

By visually capturing these varied conditions, Figure 4 emphasizes the need for more refined and adaptable models that can accurately predict electromagnetic wave behavior across such diverse and complex environments. It highlights the limitations of current

models and underscores the importance of accounting for the dynamic nature of forests when developing predictive tools for wireless communication systems.

Current research in this area often overlooks the seasonal variations of the forest medium space. Only a few studies consider these changes, typically focusing on summer and winter as two distinct seasons [31,35,36,95]. In these studies, under the assumption of constant wavelength, the forest environment is treated as a ‘black box’, where the dielectric constant within this black box is determined. Specifically, in the UHF band, this research examines the attenuation patterns of waves within the same forest and infers the dielectric constant of the forest medium space based on these nine categorizations over time periods. This approach aims to provide a universal research foundation for the dynamic development of the field, addressing the issue of strong season- and environment-specific focus in previous studies.

By broadening the scope to include a wider range of seasonal variations, this research can significantly enhance the accuracy and applicability of models predicting electromagnetic wave propagation in forest environments. This approach acknowledges the dynamic and complex nature of forests, leading to more robust and universally applicable findings in this field.

5.3. Main Research Bands for Electromagnetic Wave Transmission in Forests

The UHF (Ultra High Frequency) band has the most research, accounting for 47.06% of the total studies, indicating that it might be the most commonly considered frequency band in forest electromagnetic wave research. The VHF (Very High Frequency) and SHF (Super High Frequency) bands have fewer studies, comprising 23.53% and 15.69%, respectively, which still shows their significance in forest electromagnetic wave propagation research. The LF (Low Frequency), MF (Medium Frequency), and HF (High Frequency) bands have relatively fewer studies, making up only 7.84% of the total. This may be because these frequency bands are less critical for propagation in forest environments compared to the UHF and VHF bands. Simulation studies account for 3% of the total, indicating a research trend towards using simulation methods to explore electromagnetic wave propagation phenomena in forests. Research on X-band and Ku-band frequencies is the least presented, constituting only 1% of the total, which might reflect the limited application of these higher frequencies in forest electromagnetic wave attenuation studies, possibly due to their shorter wavelengths being more prone to attenuation in forest environments.

This research is primarily concentrated on UHF frequencies like the 2.4 GHz band and the 300 MHz to 970 MHz band. This focus on certain frequency bands underscores the importance of understanding how different wavelengths interact with forest environments, which is crucial for optimizing communication systems in such challenging conditions. Analyzing the distribution of research across these frequency bands highlights the prominence of UHF in forest wave propagation studies. This prominence is likely related to the efficiency of wave propagation in forest environments and the applicability of these frequencies in various scenarios. Such analysis can assist researchers in identifying key frequency bands for future studies and areas that may require further exploration.

5.4. Applications of Electromagnetic Attenuation Principles in Forestry Operations

In forest operations, effective communication is key for ensuring safety and improving work efficiency. Additionally, within the context of global forestry digitalization and intelligence, researching Forestry 4.0 has clear practical significance. This section introduces an electromagnetic wave attenuation model system specifically designed for forest operations. This system aims to optimize communication in forests, ensuring the accuracy and continuity of information transfer. Forest environments, with their unique geographical and climatic conditions, pose challenges to the propagation of radio waves. This model system starts from actual forest operations and comprehensively considers factors like tree density, terrain undulation, and vegetation moisture to enhance the stability and accuracy of wireless communication in forests.

Many derivations of electromagnetic formulas have not considered the canopy closure of forests, and some studies only consider tree density near the transmission point, neglecting the canopy closure and the specific forestry operational environment of the main area where signal strength changes. Considering forest environments and based on 15 years of papers, such as “Predicting wood fiber attributes using local-scale metrics from terrestrial LiDAR data: A case study of Newfoundland conifer species”, it is possible to quantify wood fiber attributes and then calculate the attenuation patterns of radio waves. LiDAR can predict forest stands. With current technology, the overall three-dimensional environment of a forest can be reconstructed through drones and LiDAR, measuring both under and over the canopy. This allows for the development of an electromagnetic wave transmission model for forest environments, which can be compared with classic multi-layer forest models and empirical models. Through field measurements and model reproduction, the effectiveness and reliability of each model can be verified in precise forest environments.

Globally, the development of intelligent forestry equipment is evolving from mechanization to intelligence. However, reliable communication in forests is a critical issue in this development. Improving the quality of communication in forests entails understanding the attenuation patterns of electromagnetic signals and combining this knowledge with effective communication systems to ensure efficient and orderly communication in forests. Machinery like multifunctional joint harvesting machines and timber collecting machines relies on communication for process visualization to monitor the wood supply chain and improve joint operation efficiency, remote fault monitoring, and ensure safety.

Taking forestry harvesting operations as an example, most forest areas lack high-speed communication network coverage. Considering the characteristics of harvesting, from the starting point to the target forest area, and upon reaching the target forest area, the changes in canopy closure are frequent, especially in deep forests. Therefore, it is necessary to study the signal attenuation model under different canopy closure conditions using field strength meters and other experimental instruments. Signal transmission in forests exhibits significant anisotropy, which is related to canopy closure and understory vegetation conditions at corresponding locations. The canopy closure of the area corresponding to forestry harvesting operations is dynamically changing, which means that the anisotropy of signal transmission is also affected. Therefore, it is necessary to monitor changes in field strength before and after harvesting, especially during the transition from the operation forest area to the log storage area and back.

Currently, the International Telecommunication Union (ITU) has not provided a specific protocol for forestry operations. The latest ITU 833.10 only considers the situation of a single, regular tree, which is the direction of most research but is not suitable for specific stages of forestry operations (harvesting (planting), collecting, unloading, squaring, etc.). Therefore, to fill this gap, research in this field has a clear prospect for application.

With the continuous development of forestry information technology and intelligence, the application of electromagnetic wave attenuation models in forest operations has become increasingly crucial. The model system introduced in this study not only provides strong technical support for communication in forests but also ensures the safety and efficiency of forest operations. Through field testing and simulation analysis, we have gained a deeper understanding of the propagation characteristics of electromagnetic waves in forests and developed communication solutions suitable for various forestry environments.

However, current research is still limited to electromagnetic wave propagation models for individual, regular trees, while actual forestry operation environments are much more complex. Therefore, future studies need to develop attenuation models that can adapt to dynamically changing canopy covers and complex terrain conditions. These models should be capable of real-time adaptation to changes in the forest, such as alterations in canopy closure after logging and the associated changes in anisotropy of signal transmission.

6. Conclusions

In the context of global climate-responsive smart forestry, supported by China's Three-North Shelter Forest Program, the need for forest thinning and selective cutting is continually increasing to ensure the health and sustainable development of the overall forest ecosystem. During forestry operations, approaches like thinning and dynamically monitoring changes in canopy closure, along with other human-induced alterations to the forest environment, are essential for basic research in forestry mechanization, informatization, and intelligentization. This has clear, practical significance for the future of forestry.

This article divides the overall research into three main parts or phases: the basic research phase, the practical simulation phase, and the innovation phase combining high-tech. The basic research phase was active during the 1960s and at the turn of the century when forestry communication technology was still maturing. Studying the forms of electromagnetic wave transmission was the primary way to improve the reliability of forest communication. This phase mainly involved categorizing the forest's medium space and considering the characteristics of wave diffraction and multipath effects in forests, offering universality in research. Studies bridging the last and current centuries mainly focused on empirical models, measuring field strength to provide specific signal-to-noise ratio attenuation formulas. Such approaches, through modeling, measuring, and modifying, could also provide an understanding of forest wireless signal transmission during those periods.

With the proliferation of next-generation wireless communication technologies (like 5G) and the widespread application of Internet of Things (IoT) devices in forestry, electromagnetic wave attenuation models for forestry operations are expected to become more complex and refined. These models will need to consider not only natural environmental factors but also the specific requirements of mechanized and automated forestry equipment. Moreover, the integration of Artificial Intelligence (AI) technologies will further enhance the predictive capabilities of these models, enabling them to learn autonomously and adapt to environmental changes and providing more intelligent decision support for forestry operations.

Each of the three main models—empirical, equivalent, and hybrid—has its own strengths and limitations, which must be considered when selecting the most appropriate model for a given application. Empirical models are valued for their simplicity and ease of use, particularly in more uniform and less complex forest environments. They allow for quick predictions and are computationally efficient. However, their oversimplification often leads to inaccuracies in more complex or dynamic forest environments. Equivalent models provide a more nuanced approach by considering multiple environmental factors, making them suitable for complex forest environments where precision is essential. These models are particularly effective in specialized forestry operations that require high accuracy. However, they demand significant computational resources and detailed environmental data, which may limit their practicality in large-scale or real-time applications. Hybrid models represent the cutting edge of current research, combining empirical and equivalent approaches with modern technologies such as LiDAR, ray tracing, and AI. These models offer the highest accuracy and can adapt to changing environmental conditions, making them ideal for advanced forestry operations. However, their complexity and resource requirements remain significant challenges for widespread adoption.

Future research should focus on overcoming the limitations of these models by developing hybrid approaches that retain the simplicity and efficiency of empirical models while incorporating the precision of equivalent models. Additionally, integrating AI and machine learning technologies will further enhance these models' predictive capabilities, allowing for real-time adaptation to environmental changes and providing more intelligent decision support for forestry operations.

Ultimately, advancements in electromagnetic wave attenuation models will greatly propel the realization of Forestry 4.0. This will not only improve the efficiency and safety of forestry operations but also contribute to sustainable forestry management and full traceability within the timber supply chain.

Author Contributions: Conceptualization, Y.M. and W.L.; methodology, Y.M.; software, D.H.; validation, Y.M., W.L., Q.L. and D.H.; formal analysis, Y.M.; investigation, Y.H. and X.B.; resources, Y.M. and D.X.; data curation, Y.M. and X.B.; writing—original draft preparation, Y.M.; writing—review and editing, W.L.; visualization, Y.M.; supervision, W.L.; project administration, W.L.; funding acquisition, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China (NSFC) Top-level Project: “Research on Path Planning and Trajectory Tracking Control Methods for Unmanned Skidding Vehicles” (grant number 31670719) and in part by the Outstanding Graduate Mentor Team Foundation of Beijing Forestry University under grant YJSY-DSTD2022009.

Data Availability Statement: These data are available with some restrictions. Some of the data in this paper are being used in other studies, and the source code of the program is being modified and upgraded and is commercially confidential, but we will publish some of the data and what research has been conducted with them in subsequent work.

Conflicts of Interest: The authors declare no conflicts of interest.

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