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INVESTIGATIONS OF FOLIAGE EFFECT ON MODERN WIRELESS COMMUNICATION SYSTEMS: A REVIEW

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Abstract—In this paper, a large number of studies of the effect of the foliage on single or lines of trees on modern wireless communication systems are reviewed. The paper is focused on the experimental works mainly done for commercial applications such as cellular communication and high speed point-to-point fixed link at the microwave and millimeter wave frequencies. For this review study, the development of the foliage loss prediction methods and the factors influencing the tree-induced shadowing effect are highlighted. In view of current research work in this area, some possible future works are proposed to improve the performance of modern wireless communication systems with the effect of foliage.

1. INTRODUCTION

The appearance of the foliage medium in the path of the communication link has found to play a significant role on the quality of service (QoS) for wireless communications over many years [1–4]. Discrete scatterers such as the randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction, and absorption of the radiated waves. This will severely constrain the design of modern wireless communication systems. From the open literature, considerable attention has been given to the influence of

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the foliage effect on the path loss, shadowing and multipath dispersion etc. Generally, the foliage effects on the wireless communications can be discussed in terms of the three following cases:

i. a tree;
ii. a line or multiple lines of trees;
iii. a forest.

The forest-induced effects on the radio-wave propagation have been studied in our previous work [4] due to the implementations of wireless sensor networks in forests recently, where the path loss prediction models are mainly discussed for long-range forested propagations in the VHF and the low UHF bands. However, the effects from a single tree and a line/multiple line of trees have not been thoroughly investigated, although some impressive studies have been conducted by several groups of researchers [1–3]. Karaliopoulos et al. [1] attempted to review some empirical foliage loss prediction models for the studies of the isolated foliage effect on a mobile-satellite channel. Bertoni [2] mainly contributed to the studies of the influence of lines of trees planted along the streets. Rogers et al. [3] performed an excellent work on the semi-empirical modeling of the foliage loss for the implementation of high speed wireless systems. It is found that these studies [1–3] focus on the investigation of the short-range foliage effect in terms of single tree/lines of trees at the microwave and millimeter waves mainly, for the commercial applications such as cellular application [1, 2] and high speed wireless communication links [3].

Recently, the rapid development of wireless sensor network [5], Multiple-Input-Multiple-Output (MIMO) [6] and Ultra Wideband (UWB) [7] techniques, and broadband high-altitude platforms (HAP) [8, 9] etc. require thorough understanding of the wireless communication channels. The above-mentioned foliage channel in terms of the single tree and line/multiple lines of trees is very common for such applicable scenarios [5–9] in rural, suburban, and urban areas. Therefore, the investigation of the foliage channel in terms of single tree/lines of trees at the microwave and millimeter waves or even higher frequencies becomes an interesting research topic.

In this paper, we will conduct a comprehensive review of the above-mentioned foliage channels at the microwave and millimeter wave frequencies. However, as the variety of operational contexts and physical situations for the foliage channels (in terms of single tree/lines of trees) are practically unlimited, the results from the many studies are often quite different. Summarizations and comparisons of the studies on the foliage loss prediction methods and the factors influencing the tree shadowing effect are carried out. This review should serve as a reference for future studies and also as a fundamental for the implementation of the modern wireless communication systems with the foliage effect. In the following, published results since 1980 are reviewed. Foliage loss prediction methods are studied in Section 2. In Section 3, tree shadowing effect and factors influencing the shadowing has been discussed. This is followed by a summarization of the wideband foliage channel information in Section 4. Finally, conclusions and some possible future works are given in Section 5.

2. FOLIAGE LOSS PREDICTION MODEL

As compared to the analytical works (mainly based on Radiative Energy Transfer (RET) theory and Wave theory) for the foliage loss predictions at the microwave and millimeter waves, there are much more empirical studies in the literature, and therefore they will be focused in the following part. Later, the analytical method will be introduced.

2.1. Empirical Method

Based on the ray geometry of the propagating wave, the foliage loss modeling and prediction with tree/lines of trees can be classified as,

i. horizontal path as shown in Fig. 1; the elevation angle is usually below 3°, and both the short foliage path through 1 or 2 trees and long foliage path through many trees (a line or several lines of trees but not form as a forest) can be experienced.

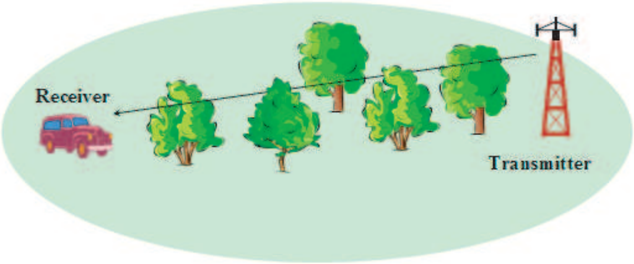

Figure 1. Schematic diagram of the horizontal foliage path.

ii. slant path as shown in Fig. 2; the elevation angle is usually above 10° and short foliage path through 1 or 2 trees.

These result in different methodologies in the modeling of the foliage-induced loss and are discussed in the following respectively.

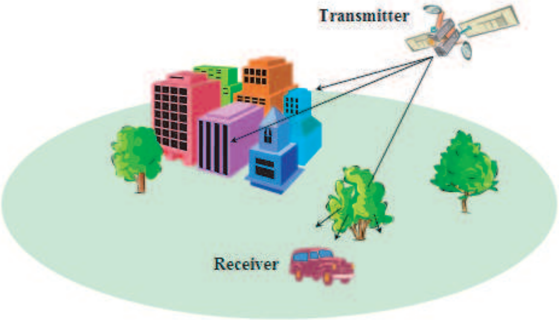

Figure 2. Schematic diagram of the slant foliage path.

2.1.1. Foliage Loss Model for the Horizontal Path

The proposed empirical foliage loss models for the horizontal propagation path can be classified as the modified exponential decay (MED) models, such as Weissberger model [10], ITU Recommendation (ITU-R) model [11], COST235 model [12] and fitted ITU-R (FITU-R) model [13]; the modified gradient model, such as Maximum attenuation (MA) model [14], Nonzero gradient (NZG) model [14], and Dual Gradient (DG) model [15]. These models are summarized in Table 1 for reference, and the review of comparative studies among these models is the focus of this subsection.

The exponential decay model was first proposed by Weissberger [10], and its main modified versions include ITU-R model [11], COST235 model [12] and FITU-R model [13] as shown in Table 1. In general, the exponential decay model has the following form,

$$L\,(\mathrm{dB}) = A \times f^B d^C \tag{1}$$

where A, B, and C are the fitted parameters from a variety of experiments with regression techniques. Different parameter values have been proposed depending on the frequency, foliage type, and propagation mechanisms etc. The advantage of the exponential decay model lies in its simplicity, but it has a major drawback that it does not take into account the measurement geometry as indicated by Savage et al. in [19].

For the developments of the modified gradient models, the NZG model was proposed by Seville et al. in [14] to overcome the zero final-gradient problem associated with the MA model. Subsequently, DG model is proposed to take into account the antenna beamwidth and the operating frequency in [15], since there is no frequency information in both the NZG model and MA model as compared to the previously discussed modified exponential decay models. However, DG model

Table 1. Summary of the main empirical foliage loss models for the horizontal path.

Model	Expression
Weissberger model [10]	$L_W\,(\text{dB}) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14\,\text{m} < d \le 400\,\text{m} \\ 0.45 \times f^{0.284} d & 0\,\text{m} \le d < 14\,\text{m} \end{cases}$ f is frequency in GHz, and d is the tree depth in meter
ITU-R model [11]	$L_{ITU\text{-}R}\,(\text{dB}) = 0.2 \times f^{0.3} d^{0.6}$ f is frequency in MHz, and d is the tree depth in meter ($d < 400\,\text{m}$)
COST235 model [12]	$L_{COST}\,(\text{dB}) = \begin{cases} 26.6 \times f^{-0.2} d^{0.5} & \text{out-of-leaf} \\ 15.6 \times f^{-0.009} d^{0.26} & \text{in-leaf} \end{cases}$ f is frequency in MHz, and d is the tree depth in meter
FITU-R model [13]	$L_{FITU\text{-}R}\,(\text{dB}) = \begin{cases} 0.37 \times f^{0.18} d^{0.59} & \text{out-of-leaf} \\ 0.39 \times f^{0.39} d^{0.25} & \text{in-leaf} \end{cases}$ f is frequency in MHz, and d is the tree depth in meter
MA model [14]	$L_{MA}\,(\text{dB}) = A_m\left[1 - \exp(-R_0 d / A_m)\right]$ A_m is the maximum attenuation, R_0 is the initial gradient of the attenuation rate curve, and d is the tree depth in meter
NZG model [14]	$L_{NZG}\,(\text{dB}) = R_\infty d + k\left(1 - \exp\left\{\frac{-(R_0 - R_\infty)}{k} d\right\}\right)$ d is the tree depth in meter, R_0 and R_∞ are the initial and final specific attenuation values in dB/m, and k is the final attenuation offset in dB
DG model [15]	$L_{DG}\,(\text{dB}) = \frac{R_\infty}{f^a w^b} d + \frac{k}{w^c}\left(1 - \exp\left\{\frac{-(R_0 - R_\infty)}{k} w^c d\right\}\right)$ The same definition for d, R_0, R_∞, and k with NZG model, f is frequency in GHz, w is the maximum effective coupling width between the transmitting and receiving antennas, and a, b, c, are estimated constant.

is not recommended. This is because the inverse relationship with frequency (f^a and $a > 0$ as in [15]) suggests a decreasing attenuation as frequency increases, which appears to contradict both the anticipated behavior and that observed in the measured data as revealed in [3]. The Version 3 of the ITU Recommendation P. 833 [16] then suggested some parameters in the NZG model to consider the frequency and the minimum width of the illuminated foliage medium.

The performance comparisons between the NZG and MA models at 11.2 GHz and 20 GHz are conducted by Stephens et al. in [17]. They reported that both the models have near identical performance when the tree is not in-leaf, while the NZG model shows better prediction ability when the foliage depth is relatively small. The evaluation of the model performance at 11.2 GHz and 20 GHz among the ITU-R model, FITU-R model, and NZG model etc. is conducted by Al-Nuaimi et al. [13]. When assessing these models, they observed that the FITU-R model produces the best prediction ability for both in-leaf and out-of-leaf generic cases as compared to others. Similar measurements are conducted at 18 GHz and 38 GHz by Mosesen [18] later. From his results, the NZG model is shown to be a better model for the foliage loss prediction considering both the tree species and foliated state.

Recently, Savage et al. [19] have conducted impressive comparative studies among the MED model, MA model and NZG model at 1.2 GHz, 3 GHz, and 11.6 GHz. It is noted that they used the original exponential decay model as shown in Equation (1) to fit the measured data for the study of the MED model. In their investigations, the measurement geometry, tree species, leaf shape and foliated state have been considered when fitting the model with the measured data. The values of A, B, and C for different experimental cases (i.e., tree species, leaf shape *etc.*) have been estimated. They reported that, on a measurement site by site basis, the NZG model gives the best prediction of foliage loss. The MA model has been found to be the worst of the three models.

From these comparative works [13, 17–19], it can be found that taking into the consideration of the measurement geometry, tree species, leaf shape and foliated state, the NZG model is the better method of the foliage loss prediction at the microwave and millimeter wave as compared to other models in Table 1. However, as pointed out by Savage et al. [19], the values obtained at one site for the NZG model may not be used to predict attenuation at another because they encompass propagation anomalies that may not exist at both sites.

2.1.2. Foliage Loss Model for the Slant Path

The research on isolated trees-induced shadowing effect was first initiated by Vogel and Goldhirsh in [20]. They conducted investigations experimentally to model the tree shadowing effects on the land mobile-satellite system. Their subsequent works [21–24] have significant contributions to this research area. In [21–24], the tree shadowing effect on the slant path at UHF, L band, and K band has been investigated respectively. The model proposed for tree shadowing effect on the slant path is first developed at UHF (870 MHz) band as

$$L_{VG}\,(\mathrm{dB}) = \begin{cases} -0.35\theta + 19.2 & \text{out-of-leaf} \\ -0.48\theta + 26.2 & \text{in-leaf} \end{cases} \tag{2}$$

where L_{VG} is the attenuation in dB, and θ is the elevation angle in degree. This model is valid for elevation angles from 15° to 40°.

Based on the measurements at UHF, L band, and K band, frequency scaling formulation relating the median attenuations of tree canopies is then developed in [23] initially as

$$L_2\,(\mathrm{dB}) = L_1\,(\mathrm{dB})\sqrt{\frac{f_2}{f_1}} \tag{3}$$

where L_1 and L_2 are the equal probability attenuations in dB at the indicated frequencies between 870 MHz and 1.6 GHz with an assumption of a full in-leaf scenario. The expression in (3) was found also to be applicable for frequencies between UHF and S Band for mobile scenarios. Based on a large amount of measured data, they [24] derived a general formula for the transition from L band (1.6 GHz) to K band (19.6 GHz) attenuation and vice-versa.

$$L_2\,(\mathrm{dB}) = L_1\,(\mathrm{dB}) \exp\left\{ b \left[\frac{1}{f_1^{0.5}} - \frac{1}{f_2^{0.5}} \right] \right\} \tag{4}$$

where L_1 and L_2 are the attenuation in dB at frequencies f_1 and f_2, respectively, expressed in GHz, and $b = 1.173$. This relationship agrees well with the measured results to within 0.2 dB when scaled from L band up to K band and 0.1 dB when scaled from K band down to L band in [24]. The above relationship is found to be applicable in the frequency range of 870 MHz to 19.6 GHz.

Recently, another scaling factor from L band (1.6 GHz) down to UHF (800 MHz) band has been determined to be approximately 1.32 as reported by Cavdar [25] based on the measurements from 14 different types of trees in Turkey. This scaling factor expression is as shown in

$$L_L\,(\mathrm{dB}) = 1.32 L_{UHF}\,(\mathrm{dB}) \tag{5}$$

where L_L and L_{UHF} are the attenuation in dB at L band and UHF, respectively.

A comparative study between Vogel and Goldhirsh's model in Equation (2) and ITU-R model was conducted by Sofos and Constantinou [26] with the measurement results at 2.5 GHz. They reported that Vogel and Goldhirsh's model fits the measurement results better when the elevation angles are higher (25.49° and 39.35° in their study, which are within the applicable range of [15° 40°] for the Vogel and Goldhirsh's model), while the ITU-R model seems to fit the measurement results better when the elevation angle is 14.03° (which is out of the range of [15° 40°] for the Vogel and Goldhirsh's model).

2.2. Analytical Method

Physics-based models to predict the foliage loss have attained significant prominence recently. As discussed by Bertoni in [2], either Radiative Energy Transfer (RET) theory or wave theory can be used to develop a proper physics-based model. In the following, the developments of the foliage loss model with both the theories are introduced.

2.2.1. Radiative Energy Transfer Model

RET theory based model is shown to be a good solution to predict the foliage loss for a variety of vegetation geometries [3], since it is time-efficient and highly accurate for the evaluation of the through-vegetation attenuation with both the horizontal and slant foliage paths. From the open literature, the application of the RET theory to model the radio-wave propagation in foliage medium was first reported in [27] and later discussed by Schwering et al. [28] and Al-Nuaimi et al. [29]. However, it is noted that the RET approach is generally applied to a homogeneous medium. In order to overcome this limitation and make it applicable to inhomogeneous foliage medium, an improved version named the discrete RET model (dRET model) is proposed by Diadascalou et al. for isolated vegetation specimens [30] and further enhanced by Fernandes et al. [31]. Comparative study on the RET model and dRET model has been conducted at 11.2 GHz and 62.4 GHz by Fernandes et al. [32] on inhomogeneous vegetation recently. The proposed dRET model was observed to perform reasonably well in terms of signal level modeling.

St Michael et al. compared the RET model with various empirical models (see Table 1) in their study [33]. They found that the RET theory based model offered the best fit to measured data at 2 GHz, while at 11.2 GHz, the ITU-R model and FITU-R model gave better fits compared to other models but the RET model still gave a reasonable fit to the observations.

The RET based model has been deeply studied by Rogers et al. in [3] and is adopted in the current ITU recommendation [34] for the modeling of foliage loss at frequencies above 1 GHz. However, this method requires four input parameters which are extracted from the path-loss measurement data, therefore makes itself a semi-empirical model in essence. Typical values of the input parameters for different tree specimen have been summarized in the current ITU recommendation [34].

2.2.2. Wave Theory Based Model

The wave theory based model is believed to be more accurate for presenting the coherence effects and phase information as reported in [38]. Coherent wave propagation models based on Monte Carlo simulation of scattering from a realistic looking fractal trees are successfully used to obtain the statistics of wave propagation through foliage in [35] and [36]. The tree stands were generated with physical and structural parameters, such as tree density, height, mean trunk diameter, etc. For the estimation of the foliage attenuation, Koh et al. [37] applied a full-wave numerical technique, Method of Moments (MoM), to calculate the scattering from a cluster of leaves or needles at 35 GHz. They reported that the widely used Foldy's approximation in conjunction with the single scattering theory overestimates the forward scattering as high as 3–4 dB at 35 GHz. Wang and Sarabandi [38] later used the distorted Born approximation to macro-model the scattering pattern from the foliage dielectric objects. By including multiple scattering effects in the simulation model, much better agreement is obtained for both mean and standard deviation of the foliage loss. In their later work [39], the effort on the reduction of the computational resources for the simulation has been carried out.

In summary, as compared to wave theory based model, the RET theory based model is numerically intractable for large propagation distances as reported in [39] due to discretization of the foliage medium into small cells. However, the RET theory based model is an appropriate prediction tool for the short-range foliage loss in radio coverage planning for cellular, fixed and satellite communication systems since it is time-efficient and also highly accurate.

3. SHADOWING EFFECT AND ITS VARIATIONS

The tree shadowing effect [40–45] often affects the modern wireless communication systems. For example, at high elevation angles, attenuation due to trees on roadside dominates fade margin requirements for the land mobile-satellite systems [40–42], whereas the presence of one or more trees on the peak of a hill can shadow the signal propagation significantly [43, 44] and even can lead to a relative enhancement of the signal by at least 10 dB at 20 GHz as compared to the diffraction loss for a path obstructed by the hill as reported in [43]. Therefore, in this part, tree-induced shadowing effect will be discussed empirically and theoretically. The focus will be on the investigations of the factors such as wind and rain which can result in a variation of the shadowing.

3.1. Empirical Characterization of the Shadowing Effect

There are a lot of empirical works addressing the characterization of the tree shadowing effect [40–45]. Typically, the foliage environments can be classified as rural [40], suburban [41, 44], and dense urban [42, 45] etc. The tree shadowing effect in dB can be directly measured as in [43–45] and also roughly predicted by the previously mentioned foliage loss models. With either of these two solutions, a fade margin for the tree shadowing can then be estimated.

There are two important environmental factors which can influence the tree shadowing effect, wind and humidity of the foliage. The wind can cause the foliage medium to move and therefore, results in the temporal variations of the received signal. Unexpected deep fades can be experienced and lead to an unacceptable QoS degradation in spite of a fade margin. While the change in the humidity of the foliage medium can vary the dielectric parameters (conductivity and permittivity) of the trees and then influence the signal propagation. From the open literature, large amount of the empirical works have contributed to the investigations of the wind induced temporal power variation [19, 46–54] and humidity increased foliage attenuation [55, 56]. They will be discussed in the following respectively.

3.1.1. Wind Effect

The contributions to the investigations of the wind effect in the literature are mainly motivated by the implementation of local multipoint distribution services (LMDS). Lewenz [46] studied the effect of the foliage movement at 2 GHz with large transmission paths (approximately 4.5 km), where the propagation path is partially blocked by trees. Four categories of wind velocity range from low to high were analyzed. It is reported that the standard deviation of the attenuation variation about the mean does increase as the wind speed increases, and for 2 GHz radio service in rural areas, a fade margin of 3.4 dB should be allowed. Later, fading characteristics of a 6 MHz channel centered at 2.545 GHz were reported by Pelet et al. [47] with a variation of wind speed. They indicated that wind impinging on the trees at velocities as low as 15 km/h can cause significant fading. On a bluff of poplar trees about four trees deep, winds of 15 km/h caused fades of 15 dB with attenuation rates up to 50 dB per second. The fades occurred at intervals as short as 0.5 seconds apart.

Naz et al. [48] conducted an investigation of wind effect on different foliated states at a much higher frequency up to 29.5 GHz as compared to the work in [46, 47]. They found that trees with green foliage (in summer) produce less variation as compared to trees with yellow and dehydrated foliage (in fall), and dense trees cause attenuation but do not produce much variation. It is also observed that, coniferous (evergreen) trees when disturbed by wind produce slower fading, while deciduous trees produce faster fading. Kajiwara [49] found that swaying foliage in wind causes a significant channel fading at 29.5 GHz, ranging over 10 dB, while the fading depth at 5 GHz is approximately 2 dB with a foliage depth of 1.6 to 1.8 m. He also reported that the attenuation in dB can be treated statistically as Rician distribution. Perras et al. [50] then performed in-depth studies of winded foliage channels over a wide range of frequencies (2.45 GHz, 5.25 GHz, 29 GHz, and 60 GHz) at relatively small transmission distances up to 110 m, where the radio channels are statistically analyzed and compared against existing channel models. It is reported that the Extreme Value and Lognormal distributions best represent the data collected, and each distribution proves better than the other in different scenarios.

A more detailed statistical analysis of the wind-induced fading is subsequently examined through the commonly known distributions associated with radio channel as shown in Table 2, namely Gaussian, Rician, Rayleigh, Nakagami, and Weibull, by Hashim et al. [51]. The wind induced temporal variation (over a short period of less than 60 seconds) is found to be Rician distributed. Moreover, they reported that the Rician K factor was found to vary exponentially with wind speed at frequencies of 0.9 GHz, 2 GHz, 12 GHz and 17 GHz in the controlled (anechoic chamber) and outdoor environments. However, different from their observations, the median Rician K factor in [52] is found to be approximately inversely proportional to averaged wind speed empirically based on the outdoor experimental data for a link up to 17 km over a period of 1 year at 3.5 GHz. Similar work for statistical

Table 2. Summary of the statistical models for the characterization of the shadowing variation used in [51].

Model	Expression
Gaussian distribution	$P_r(r) = \dfrac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(r-\mu)^2}{2\sigma^2}}$
Rician distribution	$P_r(r) = \dfrac{r}{\sigma^2} e^{-\left(\frac{r^2+s^2}{2\sigma^2}\right)} I_0\left(\dfrac{sr}{\sigma^2}\right)$
Rayleigh distribution	$P_r(r) = \dfrac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$
Nakagami distribution	$P_r(r) = \dfrac{2m^m}{\Gamma(m)\Omega^m} r^{(2m-1)} e^{-\left(\frac{mr^2}{\Omega}\right)}$
Weibull distribution	$P_r(r) = a \cdot b \cdot r^{b-1} \cdot \exp(-a \cdot r^b)$

characterization of wind-induced variation is reported by Dal Bello et al. in [53]. Recently, the relationship between the Rician K factor and averaged wind speed is found to be linear at 1.9 GHz as reported in [54].

From these works [46–54], it can be observed that the wind-induced motion of the foliage medium can vary the tree shadowing effect temporally, and the temporal variation of the shadowing can be statistically modeled. Rician K factor is usually used to characterize the temporal shadowing effect. However, the relationship of the Rician K factor referring to the wind speed is not conclusive at present, which seems to depend on the operating frequency from the literature.

3.1.2. Humidity Effect

The humidity in the tree is an important parameter which determines the dielectric constants (conductivity and permittivity) of the tree, and then influences the radio-wave propagation. Several experimental works have been conducted to investigate the humidity effect on the radio-wave propagation at different frequencies. Dilworth et al. [55] found that wet foliage produces about 6–8 dB attenuation per meter as compared to dry foliage which produces 2–4 dB per meter of attenuation. In their experiments, a variety of deciduous trees (Oak, Sycamore, and Ash) was used, and the experiment was conducted at 38 GHz. Subsequently, Seville [15] reported that there is very little difference between dry and simulated wet conditions (the water was sprayed onto the foliage to form a wet condition) on a ficus tree at 37 GHz. Dalley et al. [56] later reported that a wet leafy horse chestnut tree can produce an additional 7 dB loss at 13 GHz as compared to the dry condition.

Recently, Pelet et al. [47] observed that there was an additional attenuation of about 5 dB across a cluster of poplar trees at 2.5 GHz when there was a rain fall at a rate of 6 mm/hr. From these works [15, 47], and [55, 56], it can be found that higher humidity can increase the propagation attenuation. However, the amount of the increased attenuation is unpredictable, which depends on the operating frequency, tree specimen, etc.

3.2. Analytical Characterization of the Shadowing Effect

As compared to the empirical studies, there are limited analytical works related to the characterization of the tree shadowing effect, besides the previously discussed wave theory based method and RET theory based method. In this section, analytical methods to characterize the dynamic shadowing effect due to the swaying foliage medium by the wind and also the tree shadowing in dense urban areas, such as lines of trees planted along the streets etc., are mainly discussed.

3.2.1. Modeling of the Dynamic Shadowing Effect

Pechac et al. [57] introduced an analytical model based on a 3-D lattice, which features a flexibility to accurately simulate the temporal as well as spatial-temporal dynamic effects of a tree shadowed link. In their work, the simulated results are evaluated by both the laboratory and the outdoor measurements with dog-rose bush, apple tree, and pine. The measurement results show the efficiency of the proposed approach. The main advantages of the model are its universality and simplicity. It can be used either for the fade margin estimations for the required QoS or as a time-series generator for channel simulations as reported by Pechac et al. [57].

Another interesting work is conducted by Cheffena et al. [58] recently. They developed a new simulation model for generating signal fading due to a swaying tree, by utilizing a multiple mass-spring system to represent a tree and a turbulent wind model. The proposed model is validated with the measurements at 2.45 GHz, 5.25 GHz, 29 GHz, and 60 GHz. It is found that satisfactory agreement can be achieved.

3.2.2. Modeling of the Tree Shadowing Effect in a Street

Significant work has been contributed by Torrico et al. [59] and Bertoni [2] to model the tree shadowing effect in a street. In their works, a theoretical model is proposed to include the effects of trees as well as houses or buildings on the propagation loss in residential areas. The properties of a tree are characterized by the mean field, attenuation, and phase delay. Physical Optics (PO) method is then used to evaluate the diffracting field at the receiver by using multiple Kirchhoff-Huygens integration for each absorbing/phase half-screen combination. Trees are represented as an ensemble of leaves and branches, all having prescribed location and orientation statistics. Leaves are modeled as flat, circular, lossy dielectric discs and branches as finitely long, circular, lossy dielectric cylinders. The coherent field in the canopy is then computed by using an effective propagation constant that is determined by the medium's equivalent scattering amplitude per unit volume in the forward scattering direction. The incoherent scattered field outside the canopy is obtained in terms of an integral over the canopy volume. In this study, the effects of the trunk are neglected. A similar way to model the tree shadowing effect is recently conducted in [60, 61] up to 2 GHz. The analytical studies show good

Table 3. Characteristics of delay spread through vegetation#.

Parameters	Ginkgo	Cherry, Japanese	Trident maple	Korean pine	Himalayan cedar	Plane tree, American	Dawn redwood
Vegetation depth (m)	5.4	6.2	4.3	5.2	4.7	6.5	4.7
Delay spread (ns)	7.27	8.23	5.89	6.62	6.39	2.56	6.56

#The data in Table 3 was obtained for a 3.5 GHz carrier signal modulated with a 1.5 ns pulse. The 3 dB bandwidth of the resulting pulse-modulated signal is 0.78 GHz [34].

agreements with the results of scattering measurements for propagation through a tree canopy in a residential environment.

4. WIDEBAND FOLIAGE CHANNEL INFORMATION

Wideband foliage channel information was first investigated by Bultitude [40] for the satellite-mobile channels, where the channel impulse responses were estimated for the in-leaf and out-of-leaf conditions. However, there are limited works conducted in the literature, although the demand of the wideband foliage channel information increases recently due to the implementation of the high speed wireless systems based on the MIMO or UWB techniques. From the open literature, the most significant wideband characterizations of foliage channel are conducted by Savage et al. [19]. They investigated wideband foliage channel information with different measurement sites, different species of trees, and different measurement geometries for both the in-leaf and out-of-leaf conditions. It is found that, generally, the delay spread for in-leaf measurements was greater at 11.6 GHz than results obtained from out-of-leaf investigations. However, this was not the case at 1.3 and 2 GHz where larger values of delay spread were measured in out-of-leaf state than in-leaf, except for London Plane.

ITU Recommendation [34] has summarized some typical wideband parameters such as delay spread found for different tree specimens. These parameters are shown in Table 3 for reference.

5. CONCLUSIONS

In this paper, published works regarding the foliage effect on modern wireless communication systems have been reviewed. The foliage loss prediction model, shadowing effect and its variations, and wideband channel information are discussed both empirically and analytically.

The focus of this paper is on the development of empirical studies to date.

From the review, some possible research areas can be proposed. Since external factors such as wind, rain, etc. are found to cause the unexpected loss of the foliage shadowed links, mitigation techniques are suggested for the improvement of the reliability of these links. Some research works related to the studies of the spatial diversity have been conduced in [62, 63]. However, more research work on other diversity techniques such as depolarization [64] diversity or MIMO technique with foliage effect can be done. Moreover, for implementation of UWB techniques with the foliage effect, the wideband foliage channel information is needed to be investigated in more details.

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