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STUDY OF PROPAGATION LOSS PREDICTION IN FOREST ENVIRONMENT

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Abstract—A comprehensive review of radio wave attenuation in forest environments is presented in this paper. The classic analytical methods of propagation loss modeling and prediction are described first. This provides information on the physical processes that the radio waves undergo while propagating through a forest. The focus of this paper is on the review and summary of the experimental work done in this area and the development of empirical propagation loss prediction models. The propagation loss variation due to external factors such as antenna height-gain, depolarization, humidity effect etc. are examined and discussed individually. In view of current research work done in this area, some possible future work is proposed to improve the performance of radio links in forest environment.

1. INTRODUCTION

The increasing demand for high data rate and the limited available of bandwidth motivates the development of wireless communication through the use of Multiple-Input-Multiple-Output (MIMO) [1, 2] and Ultra-Wideband (UWB) [3] techniques. In order to predict, simulate, and design high-performance communication systems, accurate propagation characteristics of the complex environment have to be known. One of the well-known complex environment is the forest. The appearance of the foliage medium in the path of the communication link has significant effects on the quality of the received signal. This is because, discrete scatterers in the forest such as the randomly distributed leaves, twigs, branches and tree trunks can cause attenuation, scattering, diffraction, and absorption of the radiated propagating waves. This will severely constrain the design

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of communication systems, and therefore has been of interest to researchers for many years.

Since the 1960s, a significant amount of work has been done to investigate the radio wave propagation in forest environment. Both analytical and empirical work on the modeling and characterization of the forested channel have been carried out. Some useful and significant results and analysis are reported in [4]. It is reported that the foliage medium can attenuate the propagating radio wave significantly. There are many external factors that will cause the variation in radio wave propagation and even the complete breakdown of communication link in the forest.

Recently, the development of wireless sensor networks with low-power wireless transceiver for scientific and military surveillance applications within the forest environments has attracted a lot of attention. Analytical [5, 6] and experimental [7, 8] work have been performed. However, there is still a significant amount of research work that needs to be performed, especially for the empirical work [7, 8] which is site-specific, and limits the practical application of the existing research work. In order to build a robust system that operates well in dense foliage environment, the implementation of MIMO and UWB techniques is often examined. These techniques provide a potential solution to the implementation of a reliable wireless sensor network. However, the successful employment of these techniques in forest environment requires detail knowledge of the effects of the foliage medium on the propagating radio waves.

The objective of this paper is to perform a comprehensive review of radio wave propagation through the forest, with a focus on the prediction of propagation loss. This review paper should serve as a reference for future studies of forested radio wave propagation, and can also serve as a fundamental behind the implementation of modern wireless communication systems such as MIMO and UWB systems in forest environment. Published results from the year 1960 to 2009 is reviewed. Both analytical and empirical studies are included in this review. Path loss modeling and prediction in the forest is reviewed in Section 2, the variation of propagation loss due to external factors are presented in Section 3 and finally, a summary and some possible future work are proposed in Section 4.

2. PATH LOSS MODELING AND PREDICTION

2.1. Analytical Method

In 1967, Tamir [9] examined the radio wave propagation in forest environments at the band (1–100 MHz), where “a dissipative slab” is employed to describe the forest configuration. He explained the associated phenomenon over large foliage depth by a lateral wave mode of propagation. Subsequently, Dence and Tamir [10] and Tamir [11] extended the theoretical study on the propagation in forested environment with the consideration of the ground effects on radio wave propagation in the frequency range of 2–200 MHz. Unlike Tamir's original case studies done in [9], and later with Dence in [10], where both the transmitter and the receiver are located within the forest, Tamir's later work in [11] dealt with the case where either one of the terminals is located outside of the forest. In this work, he used the ray-tracing approach to deal with the radio wave propagation. With the three-layered (air layer, forest layer, and ground layer) model, recently, full-wave Parabolic Equation (PE) algorithm [12] and semi-exact solution for the received field by surface-field integration technique through an application of the equivalence or Huygen's principle [6] are implemented at VHF band to study the radio wave propagation in forest. However, unlike Tamir [11], noticeable asymmetry in the treatment of upward and downward links is experienced when one of the terminals is located outside of the forest [12]. In [6], Liao and Sarabandi report that ray-tracing in [11] provides accurate results at distant points from the vegetation truncation plane when the receiver height is large in terms of the wavelength. However, this method tends to underestimate the path loss for the case when the receiver is close to the ground. Recently, the exact Sommerfeld integral solution was successfully implemented with the three-layered anisotropic slab model at 25–100 MHz by Li and Ling [14], where the effective permittivity and conductivity of the forest layer is extracted and show considerable anisotropy and frequency dependence.

The representation of the forest as a "dissipative dielectric slab" [9–14] becomes poor for frequencies above 200 MHz where the vegetation cannot be regarded as a homogeneous medium, since the dimensions of the vegetation is at a magnitude of an order of the wavelength [11]. After successfully examining the above-mentioned three-layered model using the dyadic Green's function in [13], Cavalcante et al. then proposed a four-layered (air layer, canopy layer, trunk layer and ground layer) model in [15] to take into account the vertical non-homogeneities of the forests with the lateral wave mode for propagation when the frequency is above 200 MHz (mainly in UHF). In their work, two isotropic and homogeneous dielectric layers placed over a semi-infinite ground plane are used to represent the tree canopy and the tree trunk layers of a forest. The anisotropies are later introduced into the dielectric medium of the four-layered model by

Seker and Schneider in [16], and Seker in [17] using the Hertz potential method for the frequency range of 200–2000 MHz to improve the four-layered model proposed by Cavaleante et al. in [15].

In the more recent years, as a continued work of the analysis and study of the forest medium as a four-layered model at VHF and UHF bands, Li et al. [18–21] performed an extensive study of the radio wave propagation in a four-layered forest medium through the use of a full-wave analysis using the dyadic Green's function. All the layers in the four-layered geometry is initially assumed to be isotropic and homogeneous in [18] and [19] where the closed form of the electric fields is obtained by using the quasi-static approximation, saddle-point technique, and branchcut integration in the complex plane. Hence, the propagation of the electric fields can be expressed in terms of direct waves, multiple reflected waves, and lateral waves. Research work has also been conducted for the case where the receiver is located within the trunk layer [18] and for the case where the receiver is located within the tree canopy layer [19]. For both cases, the transmitter is located within the trunk layer. Li et al. concluded that, although the lateral waves propagating along the air-canopy, the canopy-trunk and the trunk-ground interfaces play an important role in the propagation mechanism, only the lateral wave along the upper-side air-canopy interface dominates the total field in the far zone. Subsequently, they [20, 21] further extended their study to a more general case with two electrically anisotropic layers of a canopy layer and a trunk layer for the frequency range of 200–2000 MHz.

In all the above publications, the lateral wave along the upper-side air-canopy interface is found to play a major role in the communication over a large forested depth at the VHF and the UHF bands. Lateral wave along other interfaces; the canopy-trunk and the trunk-ground etc., and multiple reflected waves from the interfaces between adjacent layers in the multi-layer models also play an important role for the radio wave propagation in forests. Moreover, Sarabandi and Koh [22] performed a study on the effect of air-canopy interface roughness on HF and VHF wave propagation in forests. The analytical formulation is based on the volumetric integral equation in conjunction with the distorted Born approximation. It is shown that the interface roughness attenuates the lateral wave slightly, and the attenuation rate increases when the Root Mean Square (RMS) height of the interface roughness is increased. Later, Liao and Sarabandi [5] extended the research work from [22] to the scenario where either the transmitter or the receiver or both, are located above the dielectric layer. In such a scenario, the Norton wave is observed. Although the Norton wave is highly localized near the air/dielectric interface, it contributes significantly as a form of radio wave propagation over forested medium.

However, as the frequency increases to high microwave and millimeter-wave, the lateral wave [9] over a large forest depth no longer exist. This is because the RMS height of the roughness of the air-canopy interface [22] increases significantly relative to the wavelength of the propagating signal. Therefore, the rough air-canopy interface attenuates the wave propagating along the treetop (i.e., the lateral wave) significantly. Since the lateral wave gets attenuated severely, the multiple-scattering [55, 56] due to dielectric objects such as branches, twigs, and leaves within the forests contributes significantly to the radio wave propagation over a large forested depth. Koh, Wang, and Sarabandi [23] applied a full-wave numerical technique, method of moment (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 attenuation rate at millimeter-wave frequencies. Wang and Sarabandi [24] later used the distorted Born approximation to macro-model the scattering pattern from dielectric objects in the forests. By including multiple-scattering effects in the simulation model, much better agreement is obtained for both mean and standard deviation of the path loss. The effect on the reduction of computational resources for the simulation is performed in their later work in [25].

Corresponding to the above approach based on wave theory, radiative transfer theory has also been used to predict and analyze the wave propagation in forests at high microwave and millimeter-wave frequencies [26]. However, the radiative transfer 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 as the discrete radiative transfer model (dRET model) is proposed by Diadascalou et al. for isolated vegetation specimens [27]. This model is further enhanced by Fernandes et al. [28]. However, this enhanced algorithm requires discretization of the foliage into small cells, and therefore, is numerically intractable for large propagation distances as reported in [25].

Through the review of these theoretical studies, it is found that these analytical models invariably require the use of numerical analysis methods to provide solutions to the intractable mathematical formulations and requires heavy computational resources. However, these physics-based models provide us with invaluable knowledge of the radio wave propagation in the forests at different frequency, and are useful for further research.

On the other hand, direct measurement provides us with the exact characteristic of the site specific communication scenarios. Based on an ensemble of measurements, empirical models can usually be developed through regression techniques. As compared to the analytical models, the advantage of empirical models is the simplicity of the final mathematical expressions that describes the scenarios and, hence, their straightforward application, although these empirical models fail to give any indication of the physical processes involved in the propagation of radio waves within the channel. In the following part, the empirical information for the propagation loss prediction in forests are focused and discussed.

2.2. Empirical Method

Many studies have been carried out to characterize and model the effects of vegetation experimentally. They have been reviewed and summarized into several well-known through-vegetation loss models, such as Weissberger's modified exponential decay model [29], ITU Recommendation (ITU-R) [30], and COST235 model [31] etc. and are summarized below.

Weissberger's modified exponential decay model [29] given in (1) is applicable where a ray path is blocked by dense, dry, in-leaf trees found in temperate climates. It is applicable in situations where propagation is likely to occur through a grove of trees rather than by diffraction over the top of the trees

$$L_w\,(\mathrm{dB}) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14\,\mathrm{m} < d \leq 400\,\mathrm{m} \\ 0.45 \times f^{0.284} d & 0\,\mathrm{m} \leq d < 14\,\mathrm{m} \end{cases} \tag{1}$$

where L_w is the vegetation loss in dB, f is the frequency in GHz, and d is the depth of the trees in meter. The difference in path loss for trees in-leaf and out-of-leaf is reported to be about 3 to 5 dB.

ITU Recommendation (ITU-R) [30] was developed from measurements carried out mainly at UHF, and was proposed for cases where either the transmitter or the receiver is near to a small ($d < 400\,\mathrm{m}$) grove of trees so that the majority of the signal propagates through the trees

$$L_{ITU-R}\,(\mathrm{dB}) = 0.2 \times f^{0.3} d^{0.6}. \tag{2}$$

COST235 model [31] which was proposed based on measurements made in millimeter wave frequencies (9.6 GHz to 57.6 GHz) through a small ($d < 200\,\mathrm{m}$) grove of trees is

$$L_{COST}(\mathrm{dB}) = \begin{cases} 26.6 \times f^{-0.2} d^{0.5} & out-of-leaf; \\ 15.6 \times f^{-0.009} d^{0.26} & in-leaf. \end{cases} \tag{3}$$

In the COST235 model (3), measurements were performed over two seasons, when the trees are in-leaf and when they are out-of-leaf.

For both ITU-R and COST235 models, L_{ITU-R} and L_{COST} are the vegetation loss in dB, f is the frequency in MHz, and d is the depth of the trees in meter.

From the study of existing established model [29–31], it is found that the through-vegetation path loss in general, can be well represented by the following expression,

$$L_{foliage}\,(\mathrm{dB}) = A \times f^B d^C. \tag{4}$$

The three parameters, A, B and C in (4) can be empirically optimized through regression techniques based on specific measured data. An optimization campaign has been carried out using measurement data at 11.2 and 20 GHz ($d < 120\,\mathrm{m}$) by Al-Nuaimi and Stephens [32], and the Fitted ITU-R (FITU-R) model is proposed as,

$$L_{FITU-R}\,(\mathrm{dB}) = \begin{cases} 0.37 \times f^{0.18} d^{0.59} & out-of-leaf; \\ 0.39 \times f^{0.39} d^{0.25} & in-leaf \end{cases} \tag{5}$$

where L_{FITU-R} is the vegetation loss in dB, f is the frequency in MHz, and d is the depth of the trees in meter respectively.

As compared to the exponential decay model [29–32], Seville and Craig [33] proposed a nonzero gradient (NZG) model at millimeter wave for high capacity point-to-point link, given in (6),

$$L_{NZG}\,(\mathrm{dB}) = R_\infty d + k\left\{1 - \exp\left(\frac{-(R_0 - R_\infty)d}{k}\right)\right\} \tag{6}$$

where L_{NZG} is the attenuation in dB, R_0 and R_∞ are the initial and final specific attenuation values in dB/m, d is the forested depth in meter, and k is the final attenuation offset in dB.

With the consideration of the site geometry, Dual Gradient (DG) model [34] is developed based on the study of the NZG model. This is achieved with using antennas of different beamwidths to accommodate the difference in the received signal levels. The DG model is then given as,

$$L_{DG}\,(\mathrm{dB}) = \frac{R_\infty}{f^a w^b} d + \frac{k}{w^c}\left(1 - \exp\left(\frac{-(R_0 - R_\infty)w^c d}{k}\right)\right) \tag{7}$$

where L_{DG} is the vegetation attenuation in dB, f is the frequency in GHz, w is the maximum effective coupling width between the transmit and receive antennas, and a, b, c are estimated constant.

A comparative study among ITU-R model, FITU-R model, and NZG model has been performed by Al-Nuaimi and Stephens [32] at 11.2 and 20 GHz. They reported that the FITU-R model yields the smallest RMS error for both the in-leaf and the out-of-leaf generic cases as compared to the measured results. Therefore, it is considered to be the best model of the three under test. Moreover, the DG model [34] is not recommended due to certain shortcomings and inaccuracies as revealed in [35] when compared to the NZG model and others.

Furthermore, as compared to the through-vegetation loss models proposed in the research studies in [29–35], for the radio wave propagation in forests, other propagating components such as ground reflected wave [36] and lateral wave [9] etc. are also needed to be considered. These have been the focus of the propagation study in forests since the 1960s.

In 1966, Burrows [37] started a prediction of the radio gain (inverse to the path loss) in a jungle at VHF band with the consideration of ground reflection as,

$$\frac{P_r}{P_t} = \left(\frac{3h_T h_R}{2d^2}\right)^2 \left(\frac{R_0}{R}\right)^2 F_s^2 F_j^2 \tag{8}$$

where R_0 is the radiation resistance of the dipole antenna in free space and R the total antenna resistance in the vicinity of the ground and foliage, F_s is the shadow factor that accounts for the effect of the curvature of the earth, F_j is the factor that accounts for the effect of the jungle, and h_T and h_R are the transmit and receive antenna heights, respectively. Transforming Equation (8) into decibels and expressing it in the path loss form yields,

$$\begin{aligned} PL_{forest}\,(\text{dB}) &= 40\log_{10}(d) - 20\log_{10}(h_T) - 20\log_{10}(h_R) \\ &\quad -20\log_{10}\left(\frac{3R_0}{2R}F_s F_j\right) \end{aligned} \tag{9}$$

The relationship between antenna height and the received power in (8) and (9) is verified in [37] through measurements performed within a tropical jungle with foliage depth of up to 6.4 km in Thailand. In the experiment, horizontally polarized antennas are used at a frequency of 100 MHz, with the transmit antenna height, h_T kept at a constant of 24.2 m, and the receive antenna height, h_R varying from 5 to 30 m.

Later, Tewari et al. [38] considered the contribution from the lateral wave at far zone and suggested the following model based on the measurements within the frequency band of 50 to 800 MHz with tropical forested depths of up to 4 km,

$$PL_{forest}\,(\text{dB}) = -27.57 + 20\log_{10}(f) - 20\log_{10}\left(\frac{Ae^{-\alpha d}}{d} + \frac{B}{d^2}\right) \tag{10}$$

where PL_{forest} is the propagation loss in forests in dB, d is the forested depth in meter, f is the frequency in MHz, α is the specific attenuation rate in dB/m, and A and B are the evaluated parameters from the measurement.

With these experience [37, 38], the researchers in [39] and [40] conducted a series of VHF and UHF experimental path loss measurements and modeling in forests with the general expression in (11),

$$PL_{forest}\,(\mathrm{dB}) = K + A\log_{10}(d) + Bd \tag{11}$$

where PL_{forest} is the propagation loss in forests in dB, K, A and B are the parameters based on measured data with regression techniques, and d is the forest depth in meter.

Recently, there is a growing interest in the near ground communications in forest areas at VHF and UHF bands due to the increase in military and scientific applications [5–7, 41, 42] etc. Therefore, a thorough understanding and modeling of the forested channel is required. Goldman and Swenson [41], Joshi et al. [7] and Meng et al. [42] started the work by performing an experimental characterization of the near ground forested path loss with a simplified expression,

$$PL_{forest}\,(\mathrm{dB}) = a + b\log_{10}(d) \tag{12}$$

where a and b are the two constants based on measured data, and the physical interpretation of b is the attenuation per decade of distance. The channel parameters estimated with (12) in [41, 42] are highly accurate but is specific to sites. For example, although the estimated b in [41] and [42] kept the same trend as frequency increases, the values for b in [42] is higher than that found in [41] over the same frequency band. Moreover, similar path loss measurements and modeling for near ground communications for cellular [43] and UWB application [8] have also been conducted in tropical and temperate forests with different tree densities, respectively. Obviously, there is no evidence that the estimated model parameters can be universally applicable.

Therefore, in order to provide a more generic empirical model, researchers in [7] and [44] started the modeling of the propagation loss in forests by combing the through-vegetation loss models and ground reflection. In [44], a comparative study among the Weissberger's modified exponential decay model, ITU-R model, COST235 model and FITU-R model with ground reflection considered, has been performed for the prediction of near ground radio wave propagation in forest at VHF and UHF band over a larger forested depth ($\sim$ 1 km). They found that, good accuracy can be achieved at short forested depth, but the prediction accuracy for all the four through-vegetation loss models with the consideration of ground reflection become poor due to the existence of the lateral wave at large forested depth, and more efforts are needed.

In a summary, both theoretical and empirical research contribution over the past 40 years on path loss modeling and prediction in forest environment is reviewed. Besides the distance law on the propagation loss in forests, other factors that causes the variation in propagation loss such as the antenna height-gain, depolarization, seasonal variation and weather etc. also plays an important role. These factors need to be considered for the radio wave propagation in forest environment. Research work done relating to these factors will be reviewed in the next section.

3. EFFECTS ON PROPAGATION LOSS VARIATION

3.1. Antenna Height-gain Effect

After the introduction of antenna height-gain on the propagation loss analytically [9] and experimentally [37, 45], Tewari et al. [46] performed an in-depth empirical modeling of antenna height-gain on the path loss in the forest. Based on the results of measurement conducted in various tropical rainforest, with foliage depths of up to 4 km in India, the empirical model is derived. Both vertically and horizontally polarized antennas at frequencies from 50 to 800 MHz are used with the transmit antenna height, h_T varying from 3.95 to 16.45 m, and the receive antenna height, h_R varying from 1.5 to 3.5 m above the ground, while maintaining the condition of $h_T \cdot h_R > 10$. They then derived the empirical antenna height-gain on the path loss in the forest as shown in (13),

$$G_h\,(\mathrm{dB}) = -12 - 4\log_{10}(f) + 20\log_{10}(h_T) + 20\log_{10}(h_R) \tag{13}$$

where G_h is the height gain factor in dB, f is the frequency in MHz, and h_T and h_R are the transmit and receive antenna heights in meter, respectively.

3.2. Depolarization Effect

Results of depolarization measurements in tropical moist deciduous and wet evergreen forests at 50–800 MHz are reported in [47]. They concluded that vertically polarized waves suffer 5 dB to 15 dB higher depolarization than horizontally polarized waves. The cross polarization discrimination (XPD), which is defined as the ratio of the amplitude of the orthogonally polarized component of the radio waves, produced by some propagation mechanism, to the amplitude of the original plane polarized waves, is found to be dependent on frequency as well as the separation distance between the transmitter and the receiver. Similar observation is also found in temperate forests by Kovacs et al. [48] at higher frequencies of 400 MHz and 1900 MHz.

3.3. Terrain Effect

The terrain effect for the radio wave propagation in forests can be classified as the plain terrain effect, and hilled terrain effect. For the plain terrain effect, analytical [18, 19] and experimental [7, 37, 44] studies show that, the ground reflection from a plain forested terrain plays a significant role on the radio wave propagation at VHF and UHF bands. The experimental results in [7, 37, 44] show that the ground reflection can result in a similar antenna height-gain effect as in [37] and [46] (proportional to $h_T^2 h_R^2$).

For the hilled forested terrain effect, Meeks [49] started the investigation of the diffraction due to a forested hill at VHF. He reported that two knife edges are sufficient to characterize the terrain diffraction in his scenario.

3.4. Humidity Effect

The change in the humidity of forests correspondingly results in a variation in the electrical constants (conductivity and permittivity) of the forests, and thereby can influence the radio wave propagation. Low [50] reported that the humidity in the tree trunks became small when there is a drastic drop in temperature to below 0°C in early February. When the humidity in the tree trunk is low, the received power at 457 MHz and 914 MHz increases by an average value of 2 dB to 3 dB, as compared to the power received when the temperature is above 0°C in January of the same year. Following this study, Evans [51] conducted measurements over a one year period at 462 MHz. He concluded that diurnal variations from wet to dry conditions (including mist) can result in a signal strength fluctuation of about $1 \sim 1.5$ dB. Changes occurs throughout the year, however, the most significant changes occurs in late summer when the foliage volume (a grove of naturally seeded, mature beech and oak trees with 150 m of diameter) is at its maximum.

Recently, a comparative study [7] of the propagation over dry and wet (due to rain) foliage conditions was conducted by Joshi et al. They reported that at 1900 MHz under wet foliage conditions, the propagation loss are approximately 29–32 dB greater than the propagation loss measured under dry foliage conditions. The foliage depth considered is between 50 m to 150 m. Later, Meng et al. [52] also performed a detailed study on the propagation over dry and wet (due to rain) foliage conditions. They reported that, the increased humidity of the forest and the accumulation of rain water in the foliage medium by the falling rain can result in additional attenuation up to 17.5 dB and 24.9 dB for 240 MHz and 700 MHz respectively in a tropical forest. The foliage depth considered is 400 m.

3.5. Seasonal Effect

For the seasonal variation of the forests, the in-leaf and out-of-leaf status of forests will be the predominant effect on radio wave propagation. The general expressions for the vegetation loss under in-leaf and out-of-leaf conditions can be obtained in [29, 31, 32].

Moreover, long term measurements (over a one year period) have also been conducted in [50] and [51]. Low [50] found that, the seasonal field-strength variation is almost independent of frequency in the UHF band, and it is also approximately the same magnitude for both the deciduous and coniferous forests. Evans [51] reported that the maximum difference between the winter (no leaf) and the late summer (full leaf) conditions is 8 dB at 462 MHz.

In a summary, external factors affecting the radio wave propagation within the forest environment is reviewed in this section. It is found that, many factors such as antenna height, depolarization etc. can affect the radio wave propagation within a forested channel. Results from these publications are useful for the planning of a reliable communication link in the forest environment. However, there exist a significant amount of research that needs to be done since most of the published results are inconclusive.

4. CONCLUSIONS

In this paper, published work regarding propagation loss prediction within the forest environment have been reviewed. Some classic analytical techniques are described to provide an insight into forested radio wave propagation. The focus of this paper is on the development of empirical models to date. It is found that, although a significant amount of research have been performed on the empirical propagation loss modeling, it is still a challenge to describe the radio wave propagation within the forest environment accurately.

From the review, some possible research areas are proposed. Since external factors such as rain etc. is found to cause the unexpected loss in communication links in the forest, mitigation techniques are suggested for the improvement of the reliability of these links. For radio wave propagation in forest, spatial diversity, first recommended by Vincent in 1969 [53] to extend the usable VHF range within the forest environment, is recently revisited by Meng in 2009 [54]. The results show that in the VHF range, signals arriving at the two receptors are highly correlated due to the appearance of the lateral wave. However, more research work on spatial diversity or MIMO technique in different propagation scenarios needs to be done.

Further research work should be done on the empirical modeling of propagation loss in forests, especially over larger forested depth. The lateral wave along the treetops and the ground reflection effect are two importance factors that requires emphasis for VHF and UHF forested propagation loss modeling. The effects from external factors such as wind and rain on the forested channel needs further study and verification. These are important research work required for building a reliable communication system operation in extreme weather conditions such as heavy rainfall and strong wind.

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