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Araştırma Makalesi Research Article

Wireless Signal Attenuation by Vegetation: Relationship Between Tree Characteristics and Signal Attenuation

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Abstract

Vegetation is a significant factor that affects the Quality of Service of radio waves. Several measurement campaigns have been conducted to predict the effect of trees on a radio wave at the micro and millimetre wavelengths. The experiments show that depth of vegetation is a major factor that contribute to signal attenuation. Furthermore, different components of the vegetation cause different behaviours of the radio wave. The empirical models did not put into to consideration the characteristics of the trees in the vegetation. The analytical approaches using wave theory have considered the vegetation characteristics, density and the geometry. This paper focuses on using existing models to characterise a vegetation based on measured parameters of a tree stand with a view to estimating the density of the foliage within a vegetation accurately. The foliage density will be used as the vegetation parameter in the wave theory model. Simulation of the signal attenuation will be conducted based on the density of the vegetation that will be estimated. The tree species selected for simulation are Pinus, Ash and Silver Birch tree species.

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1. INTRODUCTION

Trees existing on the path of a communication link was found to play a significant role in the radio signal's quality of service (QoS). They have been classified as an obstruction to the Line of Sight (LOS) between the transmitter and the receiver for many years (Al-Basheir et al., 2006; Meng & Lee, 2010; Adegoke & Siddle, 2012). This causes research on the interaction between radio waves and trees to be ongoing for several decades (Ghoraishi et al., 2013). Trees have a very complex structure composed of randomly oriented stems, branches, twigs and leaves, which causes scattering, absorption and diffraction of radio waves. The result of this causes signals to follow a different path to transmit signals to the receiver that causes the signal degradation.

Investigative studies about the effects of vegetation on radio waves showed that several factors can contribute to signal attenuation. These include; vegetation type, density, leaf state, the size of the foliage and frequency of propagation (Rogers et al., 2002; Savage et al., 2003; Ndzi et al., 2005; Al-Basheir et al., 2006; Helhel et al., 2008). Wet trees cause extra attenuation and absorption while evergreen trees have more effect on radio signals than deciduous trees (Helhel et al., 2008). Furthermore, coniferous trees are worse than broad-leaved evergreens as reported in (McLarnon, 1997; BBC & ITC, 1998). Single isolated trees may not cause major problems, but in a dense forest, the attenuation level is high. The attenuation

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level within a density of a forest per unit area depends on the distance in which the radio signal will penetrate through the forest. The shape of the Leaves and the thickness of the stems have less significant effects on radio waves at lower frequencies as the wavelength of the radio wave is larger than the thickness of the vegetation which makes easy penetration through medium. According to the CCIR report stated by (McLarnon, 1997) and the investigation carried out by (Savage et al., 2003) showed that signal attenuation by vegetation has a high dependency on frequencies. In general, trees can exist as a single or group of trees, and they can be either homogeneous or mixed tree types. This will result in the different effects they will have on radio waves even at the same frequency due to the different tree types and the geometry of the link (Ndzi et al., 2012). The different effects have become a constraint on the design of modern wireless communication systems. Figure 1 shows different modes of signal propagation through vegetation (Adegoke & Siddle, 2012)

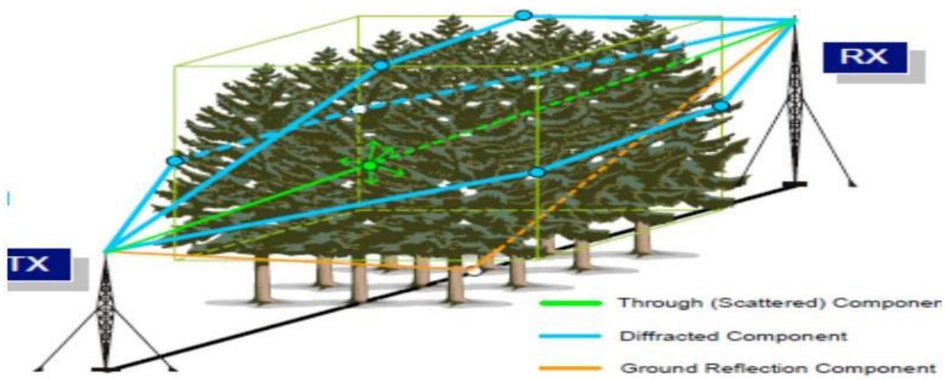

Figure 1. *Different Modes of Signal Propagation Through Vegetation (Adegoke & Siddle, 2012)*

Since the 1960s, significant research has been done with a view to developing models that will be used to predict excess attenuation of radio waves as they pass through a vegetation. Several measurement campaigns were conducted to evaluate these models. Accurate modelling of radio waves through vegetation requires a proper description of the tree geometry and foliage distribution that will be valid for wide frequency range (Ghoraishi et al., 2013). However, each measurement that has been conducted so far was based on specific tree type, climate conditions and experimental setup. Empirical and semi-empirical models have been proposed for the prediction of signal attenuation by vegetation because of their simplicity. The measurement geometry of the vegetation was not taken into account, and they do not distinguish between the modes of propagation. Most of the models proposed did not take into account the density of the vegetation (Ndzi et al., 2005; Ghoraishi et al., 2013). The major drawback of the empirical models is that they were developed based on existing data that was measured on specific tree types and in predominantly trees that grow in temperate climates. Parameters in these models are frequency, incident angles, direct-path length through vegetation. Other parameters associated with the particular environment under which measurements were performed usually computed through regression curves fitted to the measurement data (Ghoraishi et al., 2013). These measurements yielded different results when applied to different species of trees. Therefore, the performance of the models appear to be inconsistent when different link setup is being used (Ndzi et al., 2012). Mean attenuation or link budget calculation are usually what the empirical models provide (Ndzi et al., 2005). This drawback has attracted more experimental campaigns with the view of developing a generalized model to predict signal attenuation in later years.

2. REVIEW OF EXISTING MODELS

2.1. Existing Attenuation by Vegetation Prediction Models

Path losses can be modelled experimentally based on the given equation (Sabri et al., 2018), where the depth of vegetation **(d_f)** and frequency **(f)** are the parameter of path loss **(PL_{veg}). A, B**, and **C** are constant empirically determined fitting parameters.

$$PL_{veg}(dB) = A.f^{B}.d_{f}^{C} \tag{1}$$

2.1.1. Modified Exponential Decay Model (MED)

The most frequently cited prediction model was the Exponential Decay (EXD) given as;

$$L = 0.26f^{0.77}d_{f} \tag{2}$$

However, a large discrepancy was observed. Therefore, the MED model was presented to overcome some of the problems with the EXD expressed as;

$$L = \begin{cases} 1.33f^{0.284}d^{0.588}, if 14 < d \leq 400 \\ 0.45f^{0.284}d, if 0 < d \leq 14 \end{cases} \tag{3}$$

2.1.2. COST 235 and FITU-R

Cost 235 model was proposed in 1996 based on measurements conducted on grove trees at different frequencies on different tree species (COST, 1996). An improvement on the EXD model was obtained by changing the value of the fitting parameters to produce the COST 235 model.

$$L = 15.6f^{-0.009}d^{0.26}[dB] \quad \text{In-leaf} \tag{4}$$

$$L = 26.6f^{-0.2}d^{0.5}[dB] \quad \text{Out-of-leaf} \tag{5}$$

Further optimisation of the three numerical values in EXD has resulted in the Fitted ITU-R model. The measurement data by (Stephens & Al-Nuaimi, 1995) at frequencies 11.2 GHz and 20 GHz resulted in the development of the FITU-R model

$$L = 0.39f^{0.39}d^{0.25}[dB] \quad \text{In-leaf} \tag{6}$$

$$L = 0.39f^{0.18}d^{0.59}[dB] \quad \text{Out-of-leaf} \tag{7}$$

Where **f** is in MHz and **d** is in meters.

The experiment concluded the COST235 should be used when planning a Wireless Sensor Network (WSN).

The models mentioned above are exponential forms of expressions to predict excess attenuation as a function of operating frequency and length of propagation (Goldhirsh & Vogel, 1998), without considering other mechanisms that may be involved in the propagation of the signal such as, refraction and ground reflection.

2.1.3. Maximum Attenuation Model (MA)

Further investigation showed that at higher frequencies, attenuation decreased as vegetation depth increases and the gradient becomes shallower. This indicated that the scattering of the signal from tree to tree becomes a significant mode of propagation. The scattering contributes to the received signal and, therefore, reduces the effective attenuation. The measured 38 GHz data led to the suggestion that an improved model of attenuation to be given in the form (Seville & Craig, 1995);

$$A_{m} = A_{m} \tag{8}$$

Where **Am** is the maximum attenuation and **γ** is specific attenuation for very short vegetative paths (dB/m). **d** is the path within the vegetation. Specific attenuation due to vegetation, **γ** dB/m, depends on the density and species of the vegetation. This model became the ITU-R recommendation for cases where the transmitter is located outside the vegetation, and the location of the receiver is inside the vegetation for frequencies ranging from 30MHz – 30GHz (ITU, 2013). The parameter **Am** has a frequency dependency of the form

$$A_m = A_1 f^{\alpha} \tag{9}$$

Different values of $\mathbf{A_l}$ and $\boldsymbol{\alpha}$ have been used as fitting parameters depending on the species of the vegetation, frequency applied and the location.

These measurements indicate a limitation to the use of the model. Another limitation is the fixed attenuation gradient that prove not to be the desired model to be used. Therefore, the measurement geometry and methodology need to be taken into account.

2.1.4. Non Zero Gradient (NZG)

The Non-Zero Gradient (NZG) model was proposed to overcome the zero final gradient problems of the MA model for frequencies above 5GHz (Ndzi et al., 2012). The NZG model uses the initial **(R_0),** the final gradient **(R_∞),** and the offset of the final gradient **(k)** of the attenuation curve. The model also suffers from the problems associated with using values of parameters obtained from fitting curves to experimental data (Savage et al., 2003). The NZG model can be expressed in the form (Ndzi et al., 2012);

$$Att_{NZG} = R_\infty d + k\left\{1 - exp\left(\frac{-R_0 - R_\infty}{k} d\right)\right\} \tag{10}$$

The values of these parameters were obtained based on estimates carried out by Stephens in 1998. However, as pointed out by (BBC & ITC, 1998), the values of the parameters may vary with measurement sites due to propagation anomalies that are not existing in all locations (Ghoraishi et al., 2013).

2.1.5. Dual Gradient Model (DG)

The operating frequency and the beamwidth of the antenna were proposed to be taken into account in the DG model. The site geometry is taken into consideration, which considers the extent of illumination of the vegetation medium. This is characterised by the illumination width, W, the maximum effective coupling width resulting from the interaction between the transmitting and receiving antenna beamwidths inside the vegetation medium (Rogers et al., 2002). However, the DG model was not recommended because, as the frequency increases, the inverse relationship with frequency suggests a decreasing attenuation. This appears to contradict both the anticipated behaviour and that observed in the measured data (Ghoraishi et al., 2013). Therefore, the DG model proposed has proved to have several inaccuracies (Savage et al., 2003). It was concluded that further work on this model is needed to eliminate these inconsistencies. Figure 2 shows the depiction of Vegetation measurement Geometry (Rogers et al., 2002)

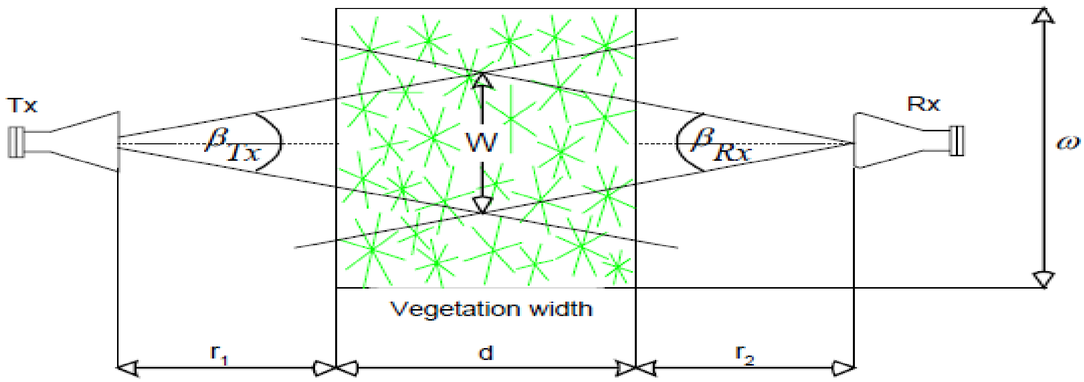

Figure 2. *Vegetation Measurement Geometry (Rogers et al., 2002)*

$$L = \frac{R_\infty}{f^a W^b} d + \frac{k}{W^c}\left(1 - e^{\left(\frac{-(R_0 - R_\infty)W_c}{k} d\right)}\right) \tag{11}$$

Where **a,b,c,k,** $\mathbf{R_0}$ and $\mathbf{R_\infty}$ are constants described in (Al-Naimi & Hammoudeh, 1993) **W** is illumination width of the vegetation medium.

2.1.6. Radiative Energy Transfer Theory (RET)

RET is one of the later approaches in predicting signal attenuation by vegetation using physics-based analysis.

The RET has been adopted in the current ITU recommendation for modelling attenuation through a vegetation for frequencies above 1 GHz, which is given by the expression below. The values of the input parameters used for different tree specimen have been summarized in the ITU recommendations (ITU, 2013).

$$L_{scat} = -10\log_{10}\left(\begin{array}{l} e^{-\tau} + \frac{\Delta\gamma_R^2}{4}\cdot\{[e^{-\hat{\tau}} - e^{-\tau}]\cdot\bar{q}_M + e^{-\tau}\cdot\sum_{m=1}^{M}\frac{1}{m!}(\alpha W\tau)^m\ [\bar{q}_m - \bar{q}_M]\} \\ + \frac{\Delta\gamma_R^2}{2}\cdot\{-e^{-\hat{\tau}}\cdot\frac{1}{P_N} + \sum_{k=\frac{N+1}{2}}^{N}\ [A_k e^{-\frac{\hat{\tau}}{s_k}}\cdot\frac{1}{1-\frac{\mu_N}{s_k}}]\} \end{array}\right) \tag{12}$$

2.1.7. Wave Theory Based Model

The wave theory-based model is believed to be more accurate for presenting the coherence effects and phase information and it has proven to have no limitation on whether the medium is homogenous or not. 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 (Meng & Lee, 2010). Physical and structural parameters, such as the height, mean stem diameter, and tree density were computer generated for the estimation of the foliage attenuation. Full wave numerical technique, Method of Moments was applied by (Koh et al., 2003) to calculate the scattering from a cluster of leaves or needles. Foldy's approximation with the single scattering theory was used, and it overestimates the forward scattering as high as 3-4dB at 35GHz as stated in the report. Based on this approach, a forest wave propagation model known as Fractal-Based Coherent Scattering Model (FCSM) has been implemented and verified successfully for a number of applications (Wang & Sarabandi, 2007).

Multiple scattering is an important factor in long distance propagation through vegetation which give drawback to the wave theory model because it is essentially a single-scattering model that has been shown (Al-Naimi & Hammoudeh, 1993) to overestimate the attenuation at high frequencies or long distances. To include high order multiple-scattering in the wave theory model, the mathematical complexity will be increased which will make it less time efficient.

2.1.8. Statistical Wave Propagation (SWAP) Model

Computing excess attenuation over long distances using wave theory even at single scattering could be time-consuming. To simplify the computation, the forest is considered as a homogenous medium along the radio wave direction and then the forest will be treated as blocks of forest as can be seen in Figure 3 (Ghasemi et al., 2013). The computation will be done on a single block and then the result will be applied to corresponding blocks. Based on this methodology, the SWAP model was developed.

The SWAP model is built on the function of wave propagation behaviour on a single block of forest, such as the relationship between the field distributions, fluctuation, attenuation on the input and output surfaces. It uses an existing FCSM model and applies to a representative block of the forest to pre-compute the propagation parameters. Network approach is used on the parameters of each block to calculate the total power at the receiver.

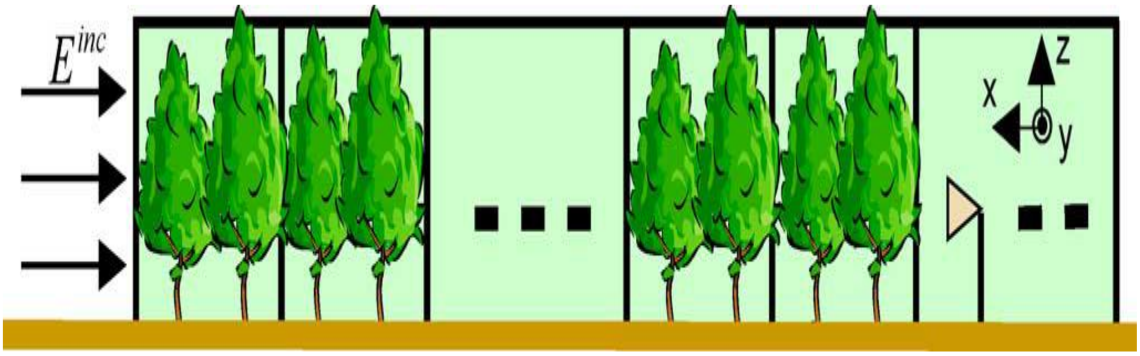

Figure 3. *A Forest Divided into Blocks of Small Similar Forests (Ghasemi et al., 2013)*

The model is evaluated on by conducting measurement on red pine stand which indicated good accuracy between the measured and simulated data (Wang & Sarabandi, 2007). They concluded that the SWAP model is quite complex and may not appeal to ordinary users. However, it can serve as the computation engine to develop a macro-model which features a simple mathematical expression relating the foliage path-loss to the foliage and radio system parameters of the specific wave propagation scenario.

2.2. Vegetation Characteristics

Understanding how trees grow in an environment is an important aspect to assess the condition of the tree. The vertical growth rate of trees allows some trees to dominate other plants.

Trees grown in urban areas are subjected to different stresses such as; compacted soil, limited space and intense pruning which affect their growth rate. The environment affects the shape and form of the trees, which makes it difficult to predict the tree height, biomass and crown dimensions than with forests where trees are much more homogenous in their growth and form for a particular environment and species (Shrestha & Wynne, 2012; Hong, 2015).

2.2.1. Tree Growth Modelling

The dimensions of tree height and crown are important tree characteristics used in many growth and yield models. Measurement of diameter at breast height of a tree is used to estimate the height of trees by using height-diameter relationship, and to determine the dominant height for measuring site productivity (Petrauskas & Rupšys, 2010; Rupšys & Petrauskas, 2010). Several pieces of research have been made to develop a reliable relationship between crown size and stem diameter, and the density of trees in a stand (Hemery et al., 2005; Vanclay, 2009). Because of the low market value of the crown, not too much attention has been put on the study of tree crowns. However, crown size is an important parameter in the studies of the growth of trees because the size of the crown determines the photosynthetic capacity of a tree (Hemery et al., 2005; Arzai & Aliyu 2010). While the crown of a tree represents the potential growth of a tree, the measurement of a tree’s crown is difficult to obtain (Lockhart et al., 2005).

2.2.2. Crown Diameter Prediction Models Using Diameter at Breast Height

Close correlation exists in principle between crown diameter and stem characteristics, such as diameter and stem characteristics.

Crown growth modelling systems are used to predict adequately the recovery from competition among trees where competition indices are not available. It is also used as a variable for stem diameter and height growth equations (Vanclay, 1994). The equations for predicting crown width of open-grown trees are known as Maximum Crown Width (MCW) equations while for stand-grown trees are called Largest Crown Width (LCW) equations. Figure 4 shows close correlation between the linear prediction model and the measure data (Hemery et al., 2005).

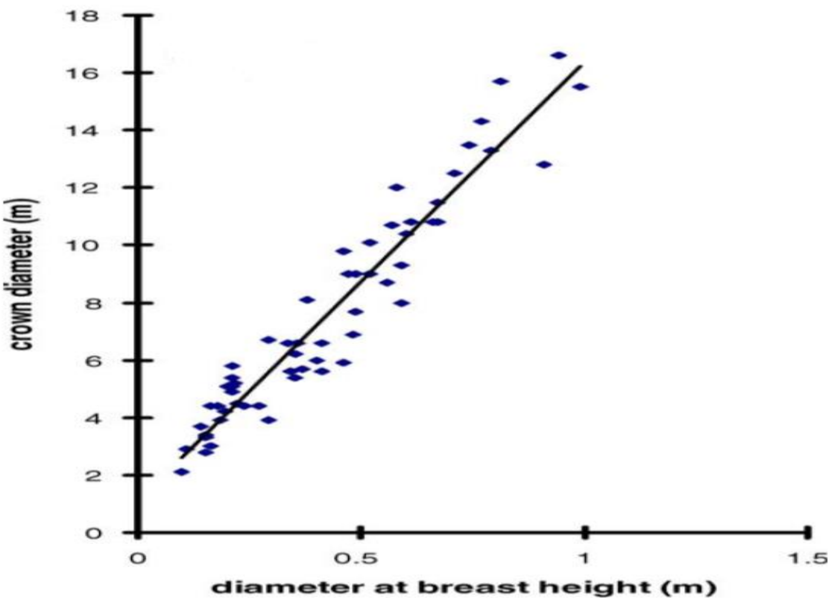

Figure 4. *Crown Diameter- Stem Diameter Relationship for Beech Tree (Hemery et al., 2005)*

Simple linear model between crown width and diameter at breast height is often adequate when modelling crown diameter equations (Hemery et al., 2005; Arzai & Aliyu, 2010; Ibrahim et al., 2014). Power functions and the monomolecular functions are used to model crown width that are nonlinear (Bragg, 2001).

Table 1 shows the summary of different prediction models developed and used to estimate crown diameter given the Stem Diameter at Breast Height (DBH) in different tree stands within a range of conditions of the stands (Burgin et al., 2011).

Table 1. *Summary of Model Equations for Estimation of Crown Diameter (width) Using DBH (Burgin et al., 2011)*

No.	Model Equation	Function type
1.	$Cw = a + b \times dbh$	Linear
2.	$Cw = a + b \times dbh + c * dbh^2$	Quadratic
3.	$Cw = a \times dbh^b$	Power
4.	$Cw = a \times b^{dbh}$	Power
5.	$Cw = a \times (1 - e^{-b*du})$	Monomolecular
6.	$Cw = (dbh/(a + b \times dbh)^2$	Hossfeld 1

Where; **Cw**; crown width (diameter), **dbh**; stem diameter at breast height, **a**, **b**, **c**; fitting parameters.

The fitting parameters are estimated for values generated by measurements conducted on different tree species. The parameters can be applied to similar species and models have proven to be applicable for a wide range on of species.

2.2.3. Tree Height Prediction Models Using Diameter at Breast Height

Tree height to DBH relationship is an important component to estimate yield, landscape appraisal and growth of trees and it is the most commonly used measurement for tree size (Sumida et al., 2013; Hong, 2015). In growth and yield modelling, height-DBH relationships are used to estimate tree's height and the tree volume can be estimated from the relationship. Many height-diameter equations have been developed for various species as can be seen in Table 2.

Table 2. *Summary of Model Equations for Estimation of Tree Height Using DBH as a Parameter*

No.	Model Equation	Source
1.	$H = 1.3 + \exp(a+b\times dbh)^c$	(Eng, 2012)
2.	$H = 1.3 + a(1-\exp(b\times dbh)^c$	(Eng, 2012
3.	$H = 1.3 + \exp(a+b\times dbh^c)$	(Wang & Hann, 1988)
4.	$Ln(H)=a+b\times dbh^{-0.2}+c\times \ln(1.3)$	(Oyebode et al., 2012)
5.	$H = 1.3 + a(1-\exp(-b\times dbh))^c$	(Corral-Rivas et al., 2014)
6.	$Ln(H-1.3) = a+b/dbh$	((Schreuder & Hafley, 1977)

Where; **H**; tree height, **dbh**; stem diameter at breast height, **a**, **b**, **c**; fitting parameters.

2.2.4. Branch Diameter and Stem Diameter Relationship

Researchers have theorized, observed and inferred that the relationship between the branch and the stem may relate to the strength of the attachment between them (Gilman, 2003), but only a few studies testing the ratio between the branch and stem diameter has been performed especially on shade tree species. In his paper, (Strickland & Goddard, 1965) observed that the greater the angle between the stem and the branch, the shorter and smaller the branch length and the diameter respectively.

It was not feasible to measure Maximum Branch Diameter (MBD) of a tree when taking forest inventories in the past. But remote sensing approaches have been ongoing to develop the relationships between the MBD with other features such as tree height, crown radius and measures of competitive status. Due to the ease in measuring the DBH of a tree, Table 3 shows different models that were developed to predict the MBD using independent variables such as DBH, crown radius, and tree height.

Table 3. *Equations for Predicting Maximum Branch Diameter*

No.	Model Equation	Source
1.	$MBD = a\times R^b\times H^c\times L^d + \varepsilon$	(Groot & Schneider, 2011)
2.	$MBD = a\times R^b\times H^c\times BA^d + \varepsilon$	(Groot & Schneider, 2011)
3.	$MBD = a\times R^b\times H^c\times BA^d\times (1+BAL)^e + \varepsilon$	(Groot & Schneider, 2011)
4.	$Ln(DBG) = p - a\times e^{-b*GUH} + \varepsilon$	(Loubère et al, 2004)

Where; **MBD**; maximum branch diameter (cm). **R**; crown radius (m). **H**; stem height (m). **L**; crown length (m). **BA**; plot basal area (m^2/ha). **BAL**; competition index, defined as the basal area of the stems larger than that of the stem in view. **DBG**; living branch diameter. **GUH**; branch insertion counted from stem apex. **a**, **b**, **c**, **d**, **e**, **ε**, **p**; fitting parameters.

The increase in MBD with height can be due to exposure of taller trees to the wind speed. Wind increases the deflection and sizes of branches (Eloy, 2011).

2.2.5. Predicting The Number of Foliage in a Tree

Trees are important components in forest ecosystems, and to understand and adequately describe such systems, quantifying various aspects of trees is necessary. There are some probability sampling strategies, particularly applicable to tree characteristics that have been used but rarely in ecological field studies (Gregoire et al., 1995). It’s hard to measure the total foliar area or mass of a tree. However, a variety of sampling methods are proposed, and estimators are presented based on the probability sampling methods (Jessen, 1955; Shinozaki et al., 1964).

Randomized Branch Sampling (RBS) is an application of multistage probability sampling, which was developed by (Jessen, 1955) to estimate the number of fruits on an individual tree. This method of sampling provides an efficient means to estimate many characteristics of trees (El-Shaarawi & Piegorsch, 2002). It can be used to estimate foliar area and mass, number of leaves, surface area of a tree and the average stem length from the butt of the main stem to a terminal bud (Gregoire et al., 1995). The RBS estimator makes use of inverse probability weighting in a way that there is no bias. Furthermore, if a random selection of branches is made with probability roughly proportional to the amount of the tree characteristic of interest (foliage, area) borne by respective branches, the estimation is very precise too (El-Shaarawi & Piegorsch, 2002).

The tree diagrammed in Figure 5a contains 27 possible paths extending from the butt of the main stem to a terminal shoot. The four branch segments of one possible path are shown in Figure 5b. RBS can be stopped after selection of a branch at any node, in which case the entire branch (3 in Figure 5c) is treated as the terminal segment of the path. RBS can also be started from the butt of any branch on a tree (Figure 5d), in which case the resultant estimates pertain only to the entire starting branch (encircled), not the entire tree (Gregoire et al., 1995).

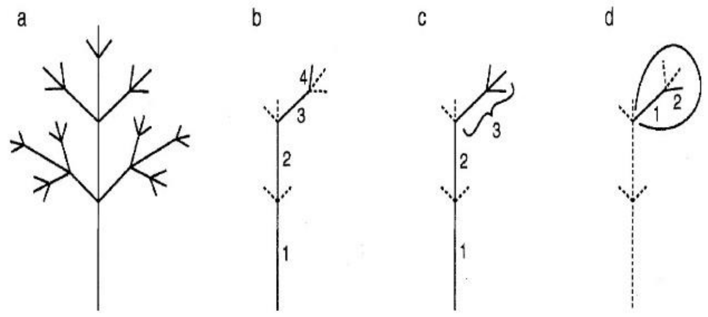

Figure 5. *Sampling of Branches in RBS (Gregoire et al., 1995)*

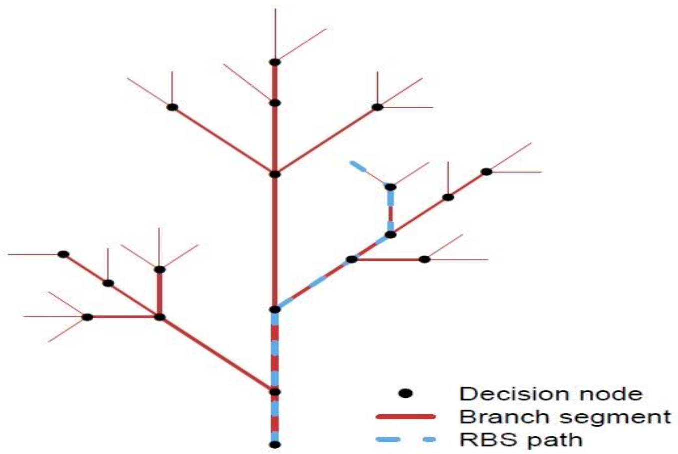

Figure 6. *Simplified Diagram of a Tree Showing One Possible RBS Path.
There are 23 Terminal Branches in This Diagram (Schlecht, 2011)*

3. INVESTIGATION AND SIMULATION SETUP

3.1. Estimation of Components

In this section, the most widely used prediction models will be adopted to estimate the components and the characteristics of trees. The tree species selected for simulation are Pinus, Ash and Silver Birch species. The foliage density of a tree stand will be used as the foliage parameter to predict the attenuation of a wireless signal due to vegetation. The plot area will be $100m^2$. The attenuation prediction model adopted will be the electromagnetic wave theory using single scatterer.

3.1.1. Crown Width Estimation Using DBH

The commonly used prediction model is the linear model given by the expression below.

$$Cw = a + b \times DBH \tag{13}$$

3.1.2. Tree Height Estimation Using DBH

As the crown width of a tree can be estimated using DBH, the height of a tree can also be estimated using the correlation between the DBH and tree height. The prediction model to estimate the height of a tree is given in the expression below.

$$H = 1.3 + a \times (1-\exp(-b \times DBH))^c \tag{14}$$

Where **1.3** is the breast height.

To predict the maximum branch diameter of a tree, the basal are of a tree is calculated. Basal area is a term used to estimate the average area occupied by trees in a given plot (usually in acres or hectares). It is defined as the total cross-sectional area of all stems in a stand measured at breast height and express as per unit plot area (e.g. m^2/ha) (Anonymous, 2015). Tree stems are usually cylindrical shape. Therefore, the cross-sectional area of stem is the same as the area of circle that which calculated as;

$$BA = \pi \times (DBH/2)^2 \tag{15}$$

Where BA is the basal area, DBH is the diameter at breast height. $\boldsymbol{\pi}$ = 3.142.

The crown height of a tree can be estimated using the estimated values of the CW and the tree height. The length of and width of a crown determines the photosynthetic capacity of a tree.

3.1.3. Maximum Branch Diameter Estimation (MBD)

The branch diameter of a tree decreases as from the crown base up to the tree apex (Loubère et al., 2004). To predict the diameter of the largest branch, crown radius, tree height, and the tree basal area can be used as parameters in the expression below;

$$MBD = a \times R^b \times H^c \times BA^d + \varepsilon \tag{16}$$

Where, **R, H, BA** are the crown radius, tree height and basal area respectively. **a,b,c,d** and $\boldsymbol{\varepsilon}$ are the estimated fitting parameter values.

3.1.4. Number of Branches and Leaves on a Tree

Randomized Branch Sampling is used to estimate different characteristics of a tree. In RBS, the main stem is also considered as a branch. Therefore, the entire above-ground component of the tree is considered as a branch comprising of several segments. A ‘path’ is defined as the sequence of the connected branch segments. The number of possible paths equals to the number of terminal shoots (Jessen, 1955). The starting point of a path can be from any butt of a branch segment (Figure 5b, c, d). RBS provides an estimate for the number of branches (or characteristics of interest). Figure 7 illustrates RBS (Anonymous, 2019).

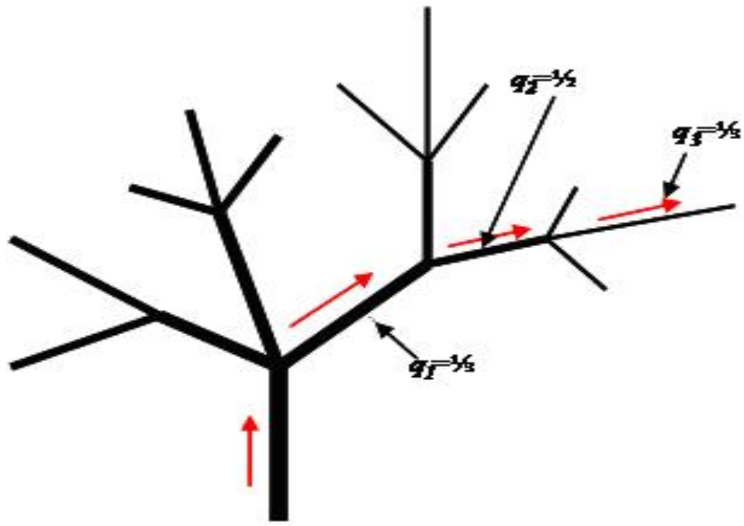

Figure 7. *Illustration of Randomised Branch Sampling (Anonymous, 2019)*

From the above diagram, $\mathbf{Q_r} = q_1 \times q_2 \times q_3$

The unconditional probability of the r^{th} branch segment selection of a path is

$$Q_r = \prod_{k=1}^{r} q_k \tag{17}$$

Where $\mathbf{Q_r}$ is the unconditional probability of the of the branch segment. If $\mathbf{f_r}$ is the number of branches in the $\mathbf{r^{th}}$ branch of the path, then the total number of branches can be estimated using;

$$\hat{F} = \sum_{r=1}^{R} \frac{f_r}{Q_r} \tag{18}$$

To estimate the number of branches on a tree, the first branch segment will be the main stem and the probabilities of each segment will be computed to give the overall number of branches. The drawback of the RBS is that at least one path must be counted manually by observing the branching system of the tree. Tree branches are formed using the phenomenon called fractal-based theory. Tree formation depends on the species, the density and the environment. The structures of tree forms can be categorized into three forms, which are; columnar, decurrent, and excurrent as can be seen in Figure 8 (Lin & Sarabandi, 1999) and Figure 9 (Anonymous, 2021).

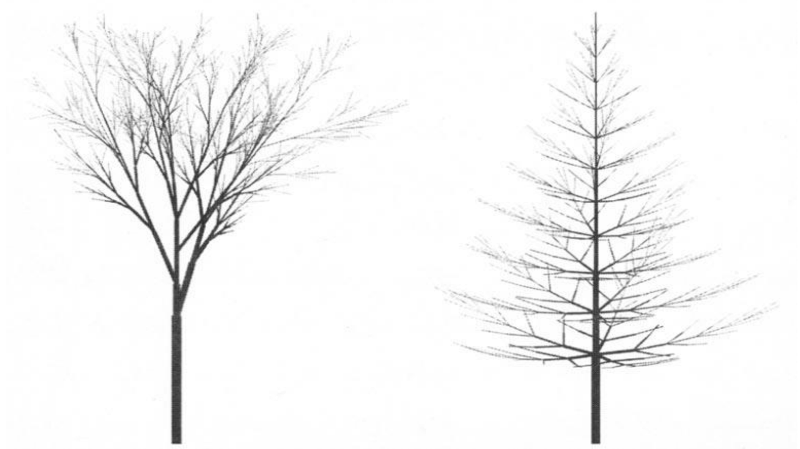

Figure 8. *Examples of Decurrent and Excurrent Types of Trees (Lin & Sarabandi, 1999)*

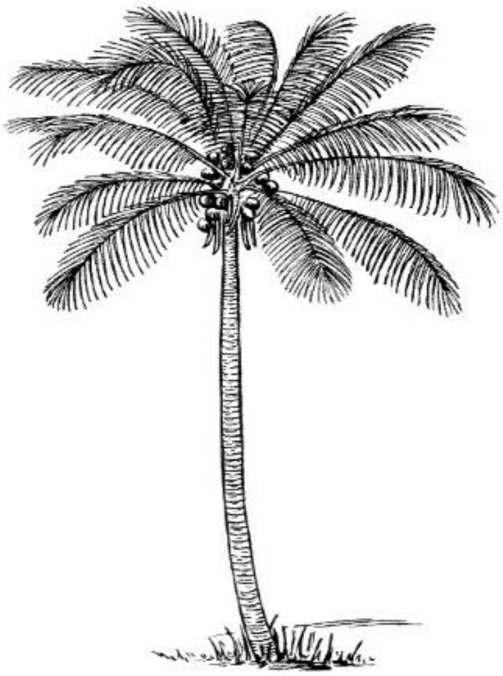

Figure 9. *Example of a Columnar Tree (Anonymous, 2021)*

The correlation of the ages between the branches **(B)** and the stems **(T)** in different tree forms can be expressed as

$$\mathbf{T= a + bB} \tag{19}$$

Where **a** is the intercept parameter and **b** is the regression slope measured for different species of particular tree forms (Eloy, 2011). The intercept is usually greater or equal to zero. A high intercept means a tree that current twigs develop from the older stems.

Decurrent trees are usually deciduous trees while excurrent trees are usually coniferous trees. In deciduous trees, the lateral branches grow faster than or sometimes as fast as the terminal shoot that give rise to the growth habit of the tree, thereby the main stem eventually disappears and forming a large crown. In conifer trees, the main stem out grows the branches giving the tree crown a cone shape.

The relationship between the radiuses of the branches formed from the main branch shows that branches become smaller than the main branch as they split to form new branches (Eloy, 2011). Another relationship is between the length of the old and the new branches given a growth rate function of the tree expressed as

$$L_b = \frac{l_a}{g} \tag{20}$$

Where $\mathbf{L_b}$ is the length of the old branch (in this case the stem) and $\mathbf{L_a}$ is the length of the new branch. **g** is the growth rate of the tree which is dependent on the species and environment (Kirtley, 2013).

To estimate the total number of branches and leaves on a particular tree using RBS, the conditional probabilities of each segment on the path should be obtained. Taking into account the growth rate of the three tree species selected for this paper, and assuming the branch formation starts at height $\mathbf{l_a}$**,** the total number of branch splits will be “$\mathbf{H\text{-}l_a /g}$**”** which will give the total number of splits in relation to the height of the tree where **H** is the breast height. Likewise, the total number of branch segment can then be estimated using “**CW /g”**.

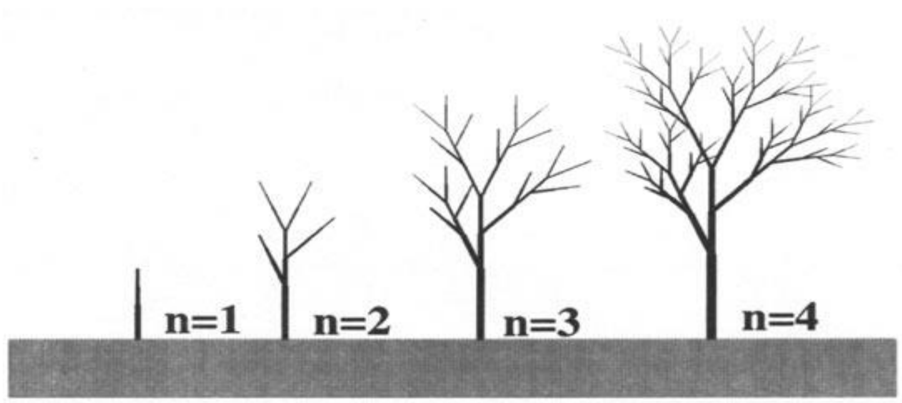

Figure 10. *Example of Fractal Branch Formation (Wang & Sarabandi, 2007)*

The leaf orientation on a twig of a tree can be examined to assume how the branches split from the main branch. The orientation angle of the branch of a tree is usually formed at 45 degrees from the main branch for broadleaves and 60 degrees angle for conifer trees (Wang & Sarabandi, 2007). Figure 11 shows examples of leaf structure of birch (a), ash (b) and pine trees (c) (Anonymous, 2020a,b,c). From Figure 11 the probability of each segment from the stem will be ½ for birch, 1/3 for ash and 1/3 for pine trees.

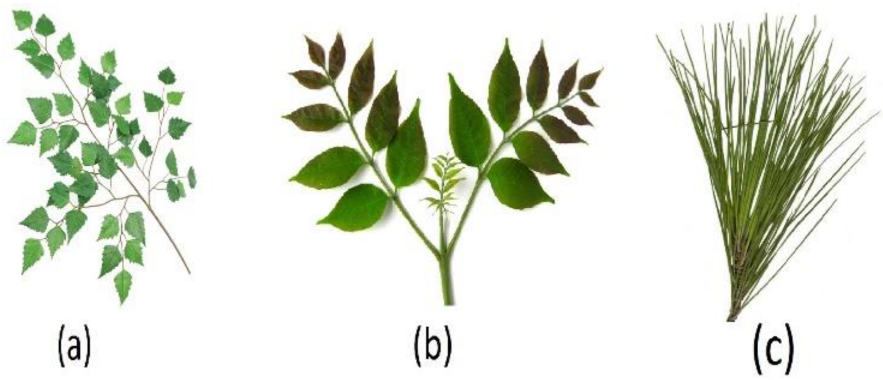

Figure 11. *Examples of Leaf Structure of* ***(a)*** *Birch,* ***(b)*** *Ash and* ***(c)*** *Pine Trees (Anonymous, 2020 a,b,c)*

Most leaves grow at the end of the twigs (the smallest branch on the tree), forming a canopy. Ash trees are broadleaved trees having a compound leaf. Meaning a leaf consisting multiple leaflets. These leaves occur in opposite pairs with the exception of the terminal leaflet (Figure 11b). The arrangement of the leaflets are typically 4-6 pairs, making a total of 9-13 leaflets (Kirtley, 2013). On each twig, there are 4 compound leaves which in total gives 36-52 leaflets on each twig. Birch leaves are similar to Ash trees, but they have larger leaflets that make four leaflets on a compound leaf and 3-4 compound leaves on each twig. Pine trees, on the other hand, have needle-like leaves 2-5 inches long. They are formed in groups of 2-5, and each group has a bundle of 2-3 needles, and each twig has average of 3-7 groups.

3.1.5. Signal Propagation Based on Wave Theory Model

The physics based FCSM model has proven to be the ideal model to predict vegetation loss due its accuracy in capturing incoherent power that is contributed by the scattering of the tree particles. A Monte Carlo simulation of scattering using computer generated fractal trees was successfully used in obtaining the propagation of a signal through vegetation (Lin & Sarabandi, 1999). The approach in the computation of the FCSM is based on Distorted Born Approximation (DBA) (Lin & Sarabandi, 1999; Wang & Sarabandi, 2005; 2007). The tree stands were generated using parameters such as trunk diameter, height, density, etc., to form a physical structure of a tree. The tree components (leaves, branches, and stem) are considered to be a group of dielectric scatterers. The scatterers are illuminated inside the forest by coherent mean-field, and the scattered fields are coherently added. The forest medium attenuates the scattered fields and likewise the illuminating field. Single scattering among the branches is computed at lower frequencies. However, at micro and millimetre wave frequencies, multiple scattering cannot be ignored (Wang & Sarabandi, 2005; 2007). In this model, the trees are categorised into deciduous or evergreen conifer trees. The only difference is the extension of the trunk into the canopy (crown) layer for evergreen trees, and either disk is used for deciduous or cylinders for conifer evergreen trees to represent the leaves and needles as depicted in Figure 12 (Burgin et al., 2011).

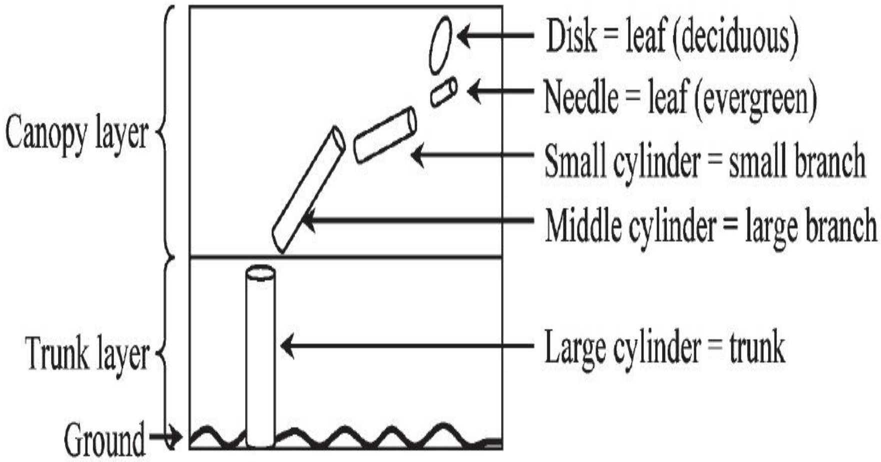

Figure 12. *Building Blocks of Scatterers for Wave Theory Model (Burgin et al., 2011)*

The boundary between the stem and the crown layer, for most trees, can be set at the first branching point where the stem divides into multiple large branches, even though the boundary is not explicitly defined. The stems are modelled as single dielectric cylinder populating the lower vertical layer. Two categories of branches are modelled as a collection of small and large dielectric cylinders in the crown layer. Depending on the type of tree, dielectric needles or disks are used to model the leaves. By obtaining the densities of the stems, branches, and leaves, lateral homogeneity is implemented over a modelling unit. The scatterers of a particular species inside each vertical layer are considered homogenous, with stationary statistics as seen in Figure 13 (Burgin et al., 2011).

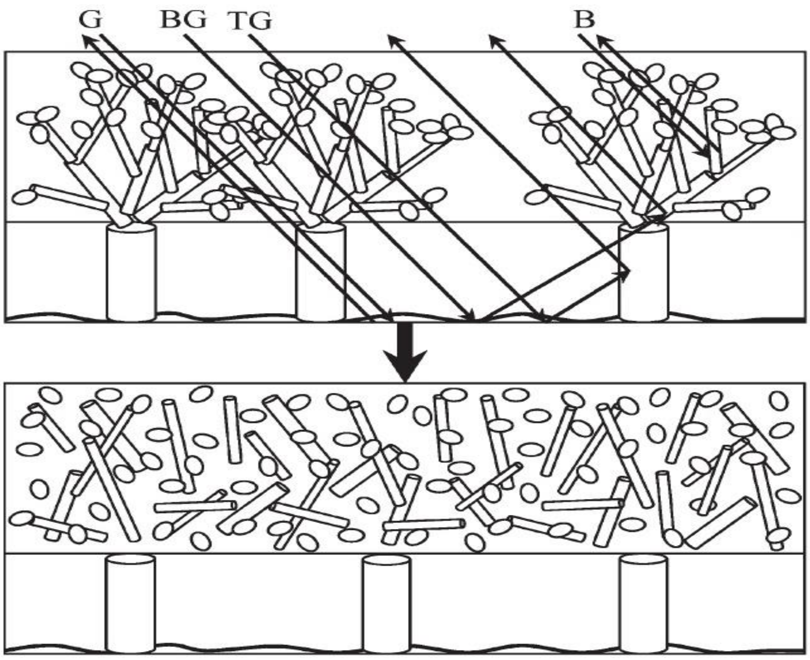

Figure 13. *Realistic Geometry of Tree Stands with Four Scattering Mechanisms (top) and the Model Realization (Burgin et al., 2011)*

Using the components of trees estimated, they are treated as a cluster of scatterers with a specific position, orientation and geometric shape and sizes (Figure 13). The entire tree is assumed to be illuminated by a plane wave with a propagation direction of unit vector k_i that is given by;

$$E^i(r) = E_0^i e^{ik_0\hat{k}_i.r} \tag{21}$$

The scattered field is calculated for individual trees since the relative position of the trees are uncertain with respect to other trees and is usually of the order of many wavelengths. Therefore, the total scattered power is determined by adding the incoherent scattered power of individual trees. To total scattered power from a tree can be computed by adding the single scattered field from each scatterer and neglecting the effect of multiple scattering among the scatterers. The propagation constant of a forest medium can be estimated using Foldy's approximation $\mathbf{M_{pq}}$ denoted by

$$M_{pq} = \frac{j2\pi n}{k_0}\langle S_{pq}\rangle \tag{22}$$

Where $\mathbf{j} = \sqrt{-1}$, **n** is the number of scatterers in a tree, $\mathbf{k_0}$ is the wave number in free space. $\mathbf{S_{pq}}$ is the amplitude of the single scatterer given by

$$\overline{E}_p^s = \frac{e^{jk_0R}}{R} S_{pq}.\overline{E}_q^i \tag{23}$$

Where $\overline{E}_p^s$ and $\overline{E}_q^i$ Are the incident and scattered fields respectively. **R** is the distance from a scatterer to a receiver that detects the scattered field. **< >** represent the average of the forward scattering amplitudes of all the scatterers in a tree. Because of the inhomogeneous nature of the tree components in the vertical direction, the tree stand can be divided into different layers in the horizontal direction, for which $\mathbf{M_{pq}}$ will be different depending on the respective geometry of the function. In conifer trees, the layers are dived into three whiles, in deciduous trees, the level is undefined. Figure 14 shows layer division of a pine stand (Wang & Sarabandi, 2007).

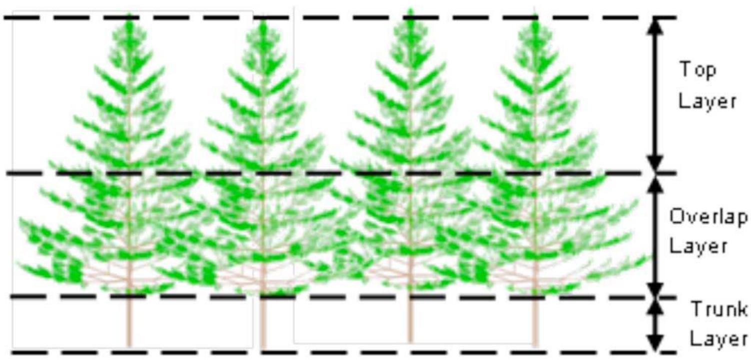

Figure 14. *Layer Division of a Pine Stand (Wang & Sarabandi, 2007)*

The scattered field is then computed from each scatterer to the receiver using equations given, with both incident and scattered field modified by Foldy's propagation constant together with free space counterparts using;

$$E = T \times E_0 \tag{24}$$

Where

$$E = \begin{pmatrix} E^v \\ E^h \end{pmatrix}, E_0 = \begin{pmatrix} E_0^v \\ E_0^h \end{pmatrix} \tag{25}$$

and

$$T = \begin{pmatrix} e^{jM_{vv}R} & 0 \\ 0 & e^{jM_{hh}R} \end{pmatrix} \tag{26}$$

E and $\mathbf{E_0}$ are the polarised electric field vectors of the radio signal propagating inside the forest medium and in free space. **v** and h are the representation of vertical and horizontal propagation. **T** is the transmissivity matrix of the effective medium with the constant of propagation $\mathbf{M_{vv}}$ and $\mathbf{M_{hh}}$, **R** is the travelled distance by the incident wave before arriving the receiver. In forest structures, the azimuthal symmetry is mostly assumed thereby making the averaged transmissivity of the depolarized components is approximately zero $\mathbf{M_{vh} \approx 0, M_{hv} \approx 0}$.

Four different mechanisms of wave propagation inside forest environments occur, which are; scattered field with the scatterer illuminated by the direct incident wave, the reflected scattered field with the scatterer illuminated by the direct incident wave, the direct scattered field with the scatterer illuminated by the reflected incident wave, and the reflected scattered field with the scatterer illuminated by the reflected incident wave. The ground effect is an important feature in FCSM which the roughness of the ground is accounted for by using Fresnel reflection coefficient (Figure 15).

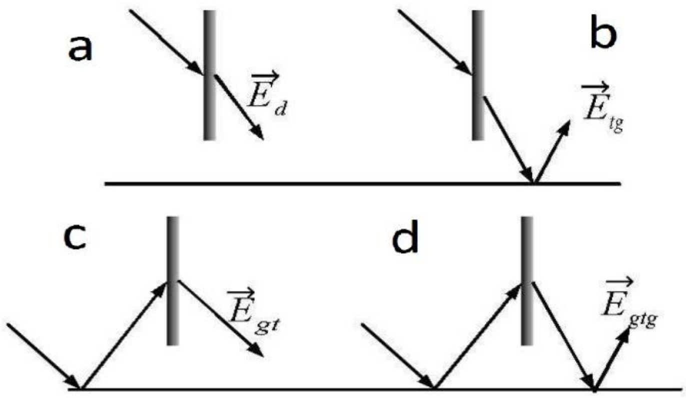

Figure 15. *Components of Scattered Field Above Ground Plane Responding to Four Wave Propagation Scenarios, **(a)** Direct-Direct, **(b)** Direct-Reflected, **(c)** Reflected-Direct and **(d)** Reflected-Reflected (Burgin et al., 2011)*

The polarization of the incident and scattered waves is a dependent point in the computation formulation of scattering from a single scatterer. The two polarizations are the horizontal and vertical polarization. Vertical polarization is assumed for this experiment where

$$\hat{v} = \hat{h} \times \hat{h} \tag{27}$$

and

$$\hat{h} = \frac{\hat{z} \times \hat{k}}{|\hat{z} \times \hat{k}|} \tag{28}$$

$\hat{z}$ and $\hat{k}$ are unit vectors of the direction of the incident or scattered wave. The total scattered field at the receiver is obtained by adding all the scattered fields of the scatterers. The same process can be followed using the given expression to calculate for leaves, branches and stems of other trees.

4. RESULTS AND DISCUSSION

The correlation between crown diameter and stem **DBH** are known to be high, so the crown diameter can be estimated using linear prediction equation. The results obtained from estimating crown width using **DBH** as the independent parameter is shown in Table 4. The density of the stand does not affect the ratio between the **CW** and the **DBH**, and the linear model is the most commonly used model because of its simplicity. From the Regression Coefficients available in literature, more data can be obtained for wide range of species as can be found in (Hemery et al., 2005; Sánchez-González et al., 2007; Arzai & Aliyu, 2010; Ibrahim et al., 2014). The results give similar correlation between Height and **DBH**. However, linear models did not yield accurate estimates (Arzai & Aliyu, 2010). This is because, the density of the stand changes the growth pattern of the tree due to the competition amongst the trees (Martínez-Vilalta et al., 2006; Sánchez-González et al., 2007; Rupšys & Petrauskas, 2010). Furthermore, at larger DBH, the estimation using linear model did not yield good correlation. Hence, the exponential model is the most ideal (Wang & Hann, 1988; Peper et al., 2001).

Predicting the diameter of the branch has not been conducted in most species. This is because the branches in a tree have no economic value, but it is used to estimate the biomass of the crown that other parameter such as the crown dimensions can be used. However, the information obtained from the results can help guide the development of pruning strategies, and likewise in radio communications, the thickness of branches is important as it also affects radio signals at high frequencies. The basal area of a tree was easily obtained. The basal area is important in estimating the branch diameter because of the gravitational force and wind force that are acting on the tilted branch angle from the stem.

Randomised Branch sampling is an effective and time efficient method of sampling tree components density compared to the conventional methods. The path selection is sampled at the longest path on the largest branch. Should the sample path selected at smaller branches, more than one path should be selected, and then the average of the sampled result is estimated. Given the higher branch segments based on the sizes of the crown, the foliage density increased as the path length increase. The variance between the estimate and the actual measured characteristic (fruits, Biomass, Foliage), it suggests that RBS can give less than ten percent (10%) variance (Jessen, 1955; Gregoire et al., 1995). The pipe Model theory (Shinozaki et al., 1964) has been used to estimate the number of leaves or branches of trees. In the model, it is viewed that each leaf is supported by a single pipe connecting the leaf through the branches and the stem to the root hairs. The pipe handles the transportation of water and other nutrients. The summary of the different parameters estimated from DBH and RBS are given in Table 4.

The FCSM model is a wave theory model aimed at predicting the path loss by considering the vegetation components as a cluster of dielectric scatterers. The input parameters for the FCSM model are in two parts;

1) The vegetation parameters and
2) The radio system parameters.

Table 4. *Summary of Different Tree Characteristics Estimated from Existing Prediction Models*

species	DBH(cm)	CW (m)	H (m)	BA ($cm^{2)}$)	MBD = $a*R^b*H^c*BA^d+\varepsilon$ (cm)	Number of branch segment(s)	Total numbe of Branches in a tree	Average leaves/needles per twig	total numbe of leaves/needles in a tree
Pine	10	1.2896	8.1234	78.55	2.3524	5	135	84	11340
	20	1.5886	13.6903	314.2	2.8018	6	405	84	34020
	30	1.8876	18.1725	706.95	3.1471	7	1215	84	102060
Ash	10	2.7938	9.9269	78.55	4.0067	6	32	36	1152
	20	4.8294	18.0708	314.2	6.0053	10	512	36	18432
	30	6.8651	24.3179	706.95	7.4983	14	8192	36	294912
Birch	10	2.5904	5.0986	78.55	2.5813	4	8	12	96
	20	4.2055	7.4878	314.2	3.2815	6	32	12	384
	30	5.8206	9.4298	706.95	3.8761	7	64	12	768

Table 5 give details of the input parameters for the FCSM. In the vegetation parameters, the Specie is not significant while the orientation of the foliage in the propagation direction is specified. However, the species determine how many likely layers the vegetation can be split into. The moisture content of the foliage is significant for determining the permittivity of the dielectric components. The crown width parameter calculates the vegetation depth along the path. In the case where multiple species are present, each species will be estimated individually.

Table 5. *Input Parameters for FCSM Wave Theory*

Vegetation Parameters			**Radio System Paramter**
Forest Stand	**Tree Structure Prameter**	**Dielectric Prameter**	
Area of the Plot	Tree height		Signal Frequency
Tree density	DBH		Tx and RX disatance
Specis type	Crown width and depth	Leaf Moisture content	Tx and RX height
	Leaf Form (needle/leaf)	Wood moisture content	Tx and Rx Polarisation
	Leaf Dimensions (cross sectional area)	Soil moisture content	
	Leaf Density		
	Tilt angle		

NB: the values in the table are estimated values which will be as vegetation parameters to predict signal loss as it passes through the vegetation

As described in the previous sections, attenuation rate corresponds to scattering of the coherent mean field by the tree components along the direction of the signal propagation. Scattering of signal through foliage also provide the advantage of redirecting part of the incident wave towards the receiver.

MATLAB R2015a was used for the simulation of the signal propagation. As predicted by researchers, Vegetation density and type are one of the major factors that affect signal propagation through vegetation. For Pinus trees, the excess attenuation is higher due to the density of components within the tree. The attenuation due to frequency does not make a significant loss at frequencies above 10GHz. This is due to the wavelength of the frequencies are at the millimetre range. Figures 16-18 show the simulation results of the attenuation levels of signals when transmitted through pinus tree, ash tree and birch tree respectively.

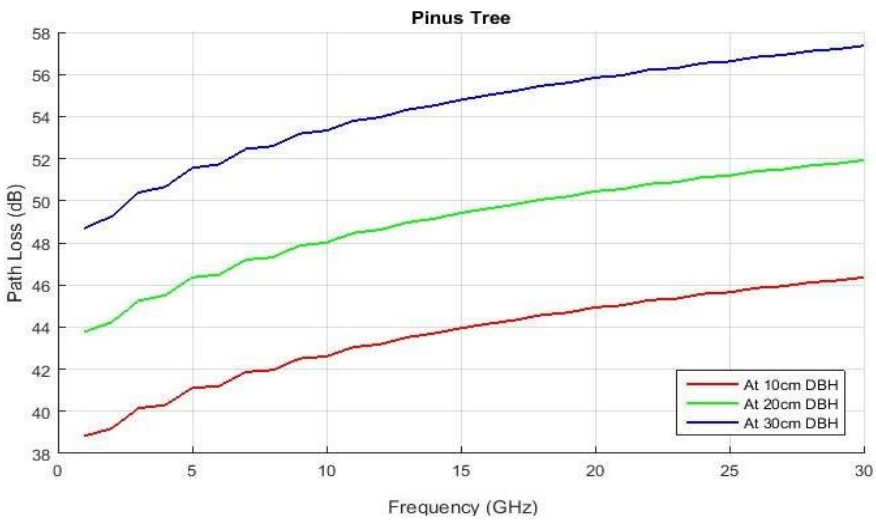

Figure 16. *Excess Attenuation of Signal in a Stand of 0.05/m^2 Density for Pinus Tree with Estimated Foliage Densities at Tree Diameter at Breast Height (DBH)*

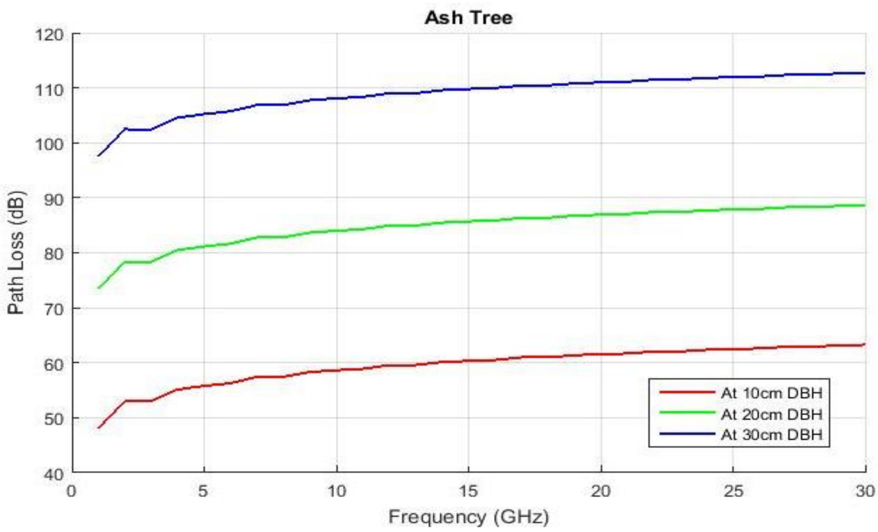

Figure 17. *Excess Attenuation of Signal in a Stand of 0.05/m^2 Density for Ash (Fraxinus Excelsior) Tree with Estimated Foliage Densities at Tree Diameter at Breast Height (DBH)*

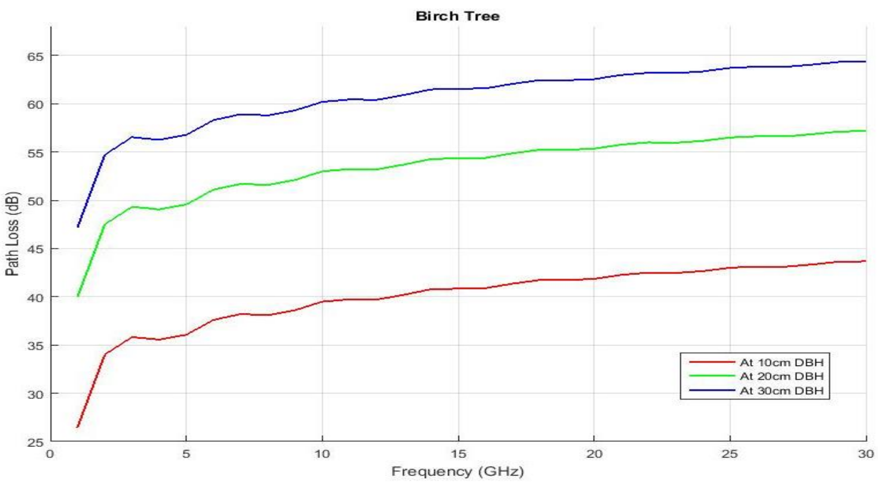

Figure 18. *Excess Attenuation of Signal in a Stand of 0.05/m^2 Density for Silver Birch Tree with Estimated Foliage Densities at Tree Diameter at Breast Height (DBH)*

The types of leaf and the size also has a significant role in signal attenuation in the sense that larger leaves produce higher attenuation as can be seen in Figure 17. Even though Ash tree has less foliage density than the Pinus tree, the path loss is higher due to the size of the dielectric scatterers. This suggests the importance of the cross-sectional area of the leaves in calculating the extent of scattering within the leaves indicating that, the larger the leaf size, the higher the attenuation. Birch trees have lower attenuation because it does not produce dense foliage as can be produced by the Pine and Ash trees.

Most of the scattering of the radio wave at the micro and millimetre waves are caused by the leaves because the thickness of the leaves is approximately equal to the wavelength. However, scattering occurs at the branch level due to the angle orientation of some of the branches, whereby causing the signal to bounce when in contact with the branch surface.

5. CONCLUSIONS

This paper includes two main parts. The first part is the study of vegetation characteristics and estimation of vegetation density components using existing models. The second part is the application of wave theory model for the prediction of signal attenuation through an estimated vegetation density.

Diameter at breast height has shown to be the strongest estimator for crown width, tree height and basal area in most tree species. Randomised branch sampling is an efficient and unbiased sampling method which was used to estimate foliage density.

Fractal-Based Coherent Scattering Model (FCSM) which is a wave theory model was adopted for the application of wave propagation through foliage. The initial model uses computer generated forest environment that in the end cannot give the actual characteristic of the foliage geometry. The coherent mean field is attenuated before hitting individual particles of the foliage by the effective medium. After the scattered field from each particle is being attenuated by the medium, they are then added by at the receiver. This in turn gives the total scattered field been attenuated by the vegetation.

The vegetation input parameter for the FCSM was replaced by the exact estimate of the vegetation using the vegetation models introduced. The experiment showed that wave theory model can be adopted as a more efficient model for wireless signal attenuation through several vegetation densities.

6. FUTURE WORK

This project work is a study work based on secondary data. The future work involves more data acquisition either secondary or measurement campaign for the vegetation modelling of more species that can satisfy a broad range of environments.

FCSM model applied, even though it provides good estimations, it is rather complex, and it is not attractable to radio link designers. Therefore, some simple formula, based on simulation results need to be developed.

Future experimental investigation should be conducted to compare the predicted path loss through a realistically measured vegetation density with the simulated path loss in an environment.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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