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A new path loss model based on the volumetric occupancy rate for the pine forests at 5G frequency band

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Abstract

In this paper, a new empirical path loss model based on frequency, distance, and volumetric occupancy rate is generated at the 3.5 and 4.2 GHz in the scope of 5G frequency bands. This study aims to determine the effect of the volumetric occupancy rate on path loss depending on the foliage density of the trees in the pine forest area. Using 4.2 GHz and the effect of the volumetric occupancy rate contributes to the literature in terms of novelty. Both the reference measurements to generate a model and verification measurements to verify the proposed models are conducted in three different regions of the forest area with double ridged horn antennas. These regions of the artificial forest area consist of regularly sorted and identical pine trees. Root mean square error (RMSE) and *R*-squared values are calculated to evaluate the performance of the proposed model. For 3.5 and 4.2 GHz, while the RMSEs are 3.983 and 3.883, the values of *R*-squared are 0.967 and 0.963, respectively. Additionally, the results are compared with four path loss models which are commonly used in the forest area. The proposed one has the best performance among the other models with values 3.98 and 3.88 dB for 3.5 and 4.2 GHz.

Introduction

Recently, the usage of wireless communication technologies in the forest and vegetation regions is significantly increased. It is vital to utilize the accurate propagation models in these regions to obtain quality communication in terms of sufficient and uninterrupted signal. These models also play an important role in the efficiency of both military and agricultural wireless applications in forest and vegetation areas [1–3].

The forest area in the world constitutes about 31% of the global land area with 4 million hectares [4]. As such rural areas have different geographical features than urban areas; it is important to focus on the studies that make up the propagation model in these areas. Studies on this subject and their high depth of analysis contribute directly to the more accurate radio frequency (RF) planning models to obtain accurate coverage. In a forest area, the signal is exposed to losses not only due to distance throughout the spread but also due to electromagnetic (EM) behaviors such as scattering, refracting, reflecting, transmission, absorbing, which occur due to tree trunk, branches, and leaves. It is even possible that these losses can be affected by the wind. Since the orientation of the branches and leaves can change due to the wind, the polarization of the propagating waves also changes [5]. These environment parameters attenuating the signals are completely non-linear in the measurement environment. Therefore, the empirical models in various forest types and locations help to obtain a more accurate coverage model.

In the literature, various publications are dealing with the theoretical and empirical propagation in forest areas. In [3], the effects of various tree height (7–12 m) and 30 cm of diameter tree trunks on path loss at 900, 1800, and 2100 MHz frequencies are investigated in the pine forest. In [6], the measurements are made for the ISM frequencies (900, 2400 MHz) in structures of various tree species when the transmitters and receivers are placed at 1.5 m of the same height. According to these, it is observed that vegetation density and tree species (i.e. pine, oak, and palm) have different effects on propagation behaviors. The scenario, which includes the receiver and transmitter at different heights, determines the effect of ground effect on the path loss. Besides, some studies are shown that the antenna height should be particularly taken into account [7–9]. Also, at higher frequencies, since the branches and leaves of the trees are larger than the wavelength, there can be more scattering, and propagation loss increase [2, 9]. It should be noted that whether the trees in the forest have regular distribution effects the level of the path loss [10]. In general, even though most of the studies are carried out for foliage depths ranging from ~10 to 800 m, there is also one study that measures path loss up to 8 km [11]. However, while scenarios with higher foliage depth are expected to increase the path loss, it is found to decrease due to the lateral wave effect [1]. While the studies are generally carried out throughout the forest, there are also limited studies carried out with a single tree. In this way, the effects of the trunk, branches, and leaves on a single tree on EM propagation behaviors are revealed [12–14].

It is important to guide the coverage planning studies in 5G technology. To the best of our knowledge, studies in the 5G frequency band in forest areas are very limited [15, 16]. It is worth mentioning that both foliage density and moisture content of soil contribution play an important role in RF propagation as remote sensing applications [17]. In this study, the measurements are carried at 3.5 and 4.2 GHz in the 5G frequency region in the pine trees environment near Golcuk Lake, Turkey. Using the measurement results, a new empirical path loss model based on the frequency, distance, and the volumetric occupancy rate (v) is generated. This study aims to determine the effect of v on path loss depending on the foliage density in the forest area consisting of pine trees, unlike the models in the literature. Section 'Fundamentals of foliage path loss models' mentions the theoretical background of path loss models in propagation studies. Section 'Measurement environment' includes the test and measurement environment to generate the path loss model while Section 'The generation of the new path loss model' reports on the results of measurement and verification of the proposed model. Section 'The results and model performance' concludes the comparison of the performance of the models.

Fundamentals of foliage path loss models

Theoretical formulations explaining propagation behaviors in non-line-of-sight (NLOS) measurements, which depend on various attenuation parameters, are very complicated to understand [10, 18–22]. For this purpose, models based on empirical formulation generated from the measurement results at different frequencies are quite common. These models are classified into two categories such as mainly modified exponential decay (MED) and log-normal models. Some studies measure the size of foliage depth and create a model with location-based image processing [22]. In MED models such as Weissberger, ITU Recommendation (ITU- R), LITU-R, FITU-R, and COST235 [23–29], the path loss changes as an exponential function of frequency and distance. It should be noted that these five models are made in areas with foliage depths <1 km. The general form of the path loss in forest areas can be shown in (1).

$$PL_{forest}(\mathrm{dB}) = a \times f^{b}\, d^{c} \tag{1}$$

where a, b, and c values are constants. In the Weisberger model, f is the frequency in GHz, while in the other four models, f represents the frequency in MHz, and d is the distance in meters for all. Weisberger model in (2) is obtained by measuring in dry air from leafy trees in temperate climates. Here, this model is valid for two distance intervals (0 m < d < 14 m and 14 m < d < 400 m).

$$PL_{W}(\mathrm{dB}) = \begin{cases} 1.33 \times f^{0.284} d^{0.588} & 14\mathrm{m} < d < 400\mathrm{m} \\ 0.45 \times f^{0.284} d & 0\mathrm{m} < d < 14\mathrm{m} \end{cases} \tag{2}$$

The ITU-R model obtained by measuring the UHF frequency in an area with a depth of 400 m is given in (3).This model is applied between 200 MHz and 95 GHz [28].

$$PL_{ITU\text{-}R}(\mathrm{dB}) = 0.2 \times f^{0.3} d^{0.6} \tag{3}$$

The FITU-R model is obtained from with leaf and without leaf palm in the 11.2–20 GHz band as given in (4).

$$PL_{FITU\text{-}R}(\mathrm{dB}) = \begin{cases} 0.39 \times f^{0.39}\, d^{0.25} & \text{in leaf} \\ 0.37 \times f^{0.18}\, d^{0.59} & \text{out of leaf} \end{cases} \tag{4}$$

The LITU-R model is developed for leafy trees and also takes into account the effect of the lateral wave. It is obtained by modifying the ITU-R model as given in (5).

$$PL_{LITU\text{-}R}(\mathrm{dB}) = 0.48 \times f^{0.43}\, d^{0.13} \tag{5}$$

The COST235 model is developed by measuring the leafy and leafless trees and is obtained by measurements in the range of 9.6–57.6 GHz as given in (6).

$$PL_{COST}(\mathrm{dB}) = \begin{cases} 15.6 \times f^{-0.009}\, d^{0.26} & \text{in leaf} \\ 26.6 \times f^{-0.2}\, d^{0.5} & \text{out of leaf} \end{cases} \tag{6}$$

Measurement environment

According to the data gathered in a research in 2019 [30], about 30% of Turkey (22.621 million hectares) is covered by forests. The reference measurements conducted to create a path loss model are carried out in Golcuk Nature Park, located 1300 m above sea level, in the southwest of Isparta. The coordinates of this region are 37° 44′ 03.70″N and 30° 29′59.00″E. As seen in Fig. 1, three areas with flat ground and covered with pine trees are selected to carry out measurements. In Fig. 1, the location of the reference measurements made to generate a new path loss model is given. To increase the accuracy of the measurements, they are conducted in three different locations with similar features in this region, and their average values are taken Fig. 2. T_x and R_x are abbreviations of transmit and receive antenna, respectively. While T_x is stable, R_x is moved in the main direction of T_x.

The block diagram containing the test equipment used in measurements for both 3.5 and 4.2 GHz is given in Fig. 2. While the Signal Hound VSG60A model operating in the 50 MHz–6 GHz range is used as a vector signal generator, the Minicircuit ZVA-183X-S+ model operating in the range of 700 MHz–18 GHz and having a gain of 26 dB is used as an RF pre-amplifier. A-info LB-10180 double-ridged horn antennas with 1–18 GHz frequency range and 11 dBi of gain are used as transmitter and receiver antennas with horizontal polarization. Signal Hound USB-SA44B model operating in the range of DC-4.4 GHz is preferred as a spectrum analyzer. Also, the new path loss model based on the reference measurement data is obtained by using the curve-fitting method in Matlab®.

The signals received from the spectrum analyzer are obtained on the computer thanks to Spike software. While the strength of the received signal for 3.5 GHz is −51.78 dBm and the frequency span 100 MHz, amplitude reference level is −10 dBm and amplitude division is 10 dB. It should also be noted that the noise level is −90 dBm.

Related measurements

There are some publications in the literature that make path loss measurements of pine forest areas and suggest a limited number of models. The summary of the related measurements is given in Table 1. The studies mostly investigate the effect of tree types, antenna types [31], the heights of antennas, the distance, and

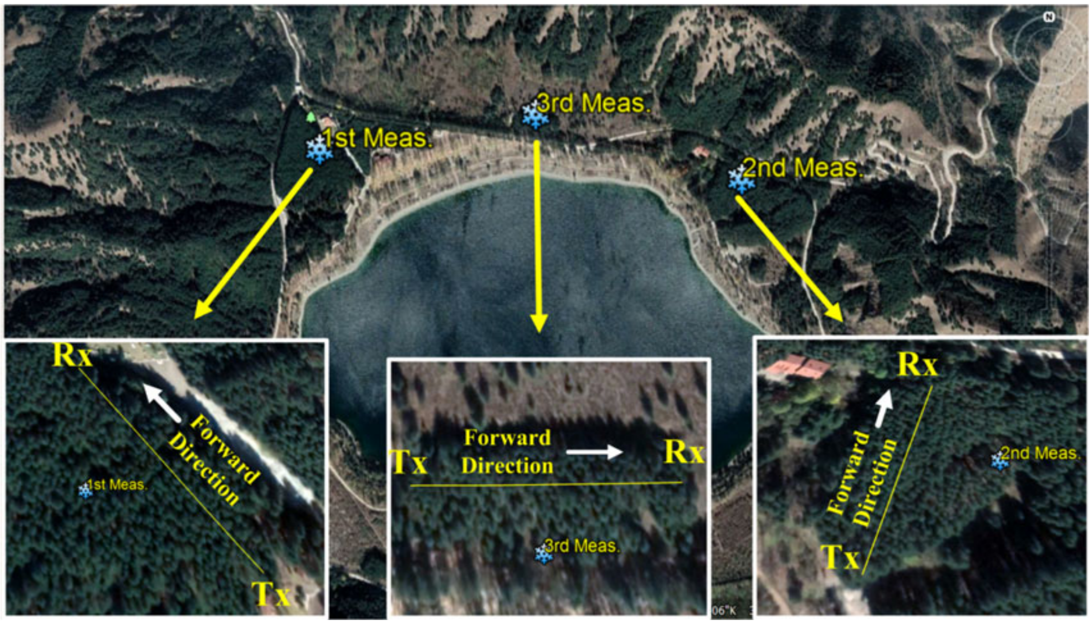


Fig. 1. Reference measurement region used to generate a path loss model.

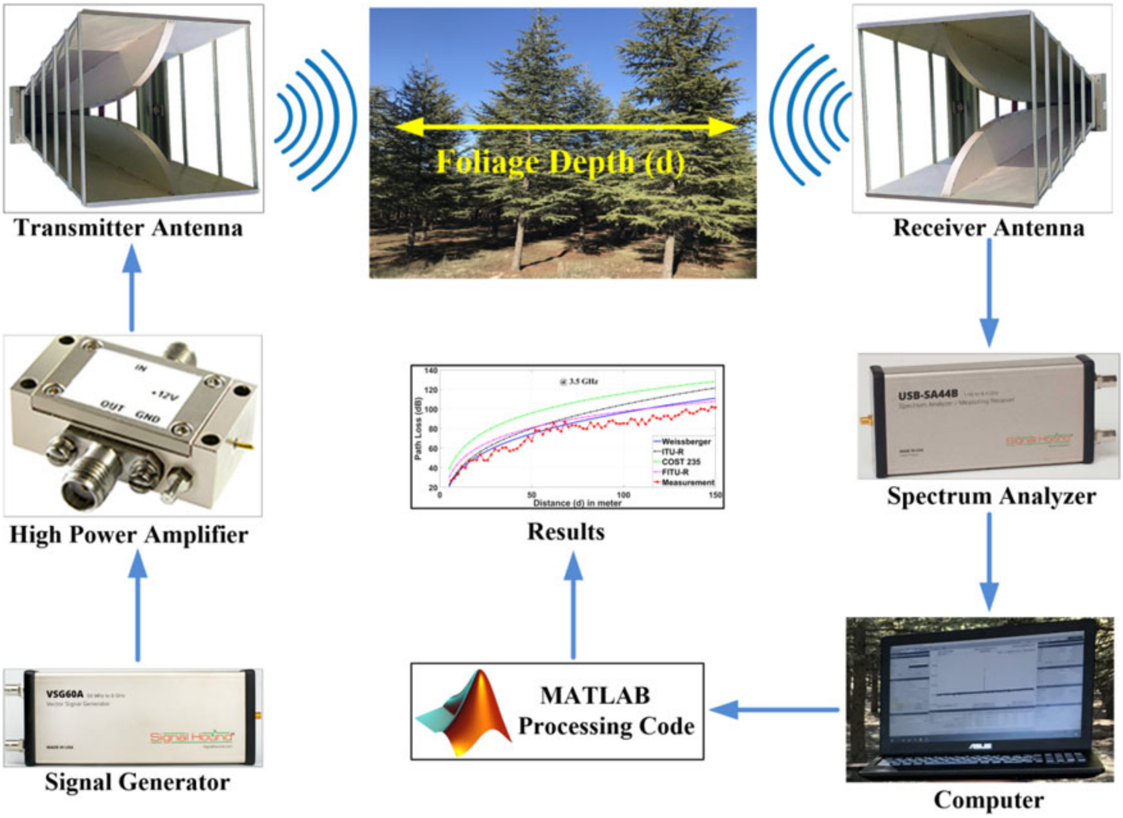


Fig. 2. Block diagram containing test equipment.

frequency on the foliage path loss. In this study, unlike other studies, the new path loss model based on v in the pine forest is proposed in the 5G frequency band. In measurements, T_x and R_x are selected as directional horn antennas and both are placed on a 2 m tripod.

The generation of the new path loss model

Most of the models in the literature are insufficient since they depend only on the frequency and the distance. In addition, there is a certain foliage density in the regions where the models

Table 1. Summary of the related measurements.

Tree types in the forest	The effect on path loss examined	Frequency (MHz)	Max. range (m)	The height of T_x and R_x (m)	Antenna types	New model	Ref.
Coniferous and deciduous trees	Effects of antenna heights	917.5	$d < 2500$	1.5, 2.5 and 3.5	Folded dipole	–	[1]
Pine trees	Effect of tree trunk height	900, 1800, and 2100	$d < 400$	2	Omni-directional	Yes	[3]
Pine trees	Effect of tropical plants on path loss	700, 750, and 800	$d < 100$	T_x: 1.5 and 6.12, R_x: 1.5	–	Yes	[5]
Coniferous and deciduous trees	Effects of the antenna types	2400	$d < 1000$	1.8	Omni- and directional	–	[10]
Pine, oak and deciduous trees	Antenna heights at the different frequencies	2400, 3500, and 5800	$d < 150$	1.6	Omni-directional	–	[14]
Coniferous trees	Effects of foliage depth	28 000	$d < 100$	–	–	Yes	[16]
Pine trees	Effect of the scattering	35 000	15 × 25	1.3	Horn	–	[19]
Pine trees	Effect of the volumetric occupancy rate	35 000 and 42 000	$d < 150$	2	Horn	Yes	This study

are valid. These models are not valid in regions where there are different densities. Therefore, unlike the other studies, the new path loss model including the foliage density (called as volumetric occupancy rate) in addition to distance and frequency is proposed in this study. For this, the measurements in Golcuk Lake and Suleyman Demirel Campus are made to create the model and verify the performance of the model, respectively.

The path loss model based on volumetric occupancy rate

As EM waves propagate into the foliage environment, they attenuate at a certain distance. The decrease in signal power of EM wave due to the obstructions of the line of sight (LOS) can be defined as path loss [1, 3]. This concept is very important to gain insight into the performance of the system such as a wireless sensor networks. While the loss in free-space depends on frequency and distance, the path loss of environments such as vegetation fields also depends on various EM parameters such as scattering, multipath fading, diffraction, refraction, and reflection. Also, the EM characteristics of medium (materials, vegetation environment) such as dielectric constant affect these EM parameters [32–35]. The path loss can simply be shown in (7).

$$P_{PL} = P_t - P_r \text{ (Watt)} \tag{7}$$

where P_t and P_r are the power values of the transmitter and receiver, respectively. The path loss in free-space is also given in (8).

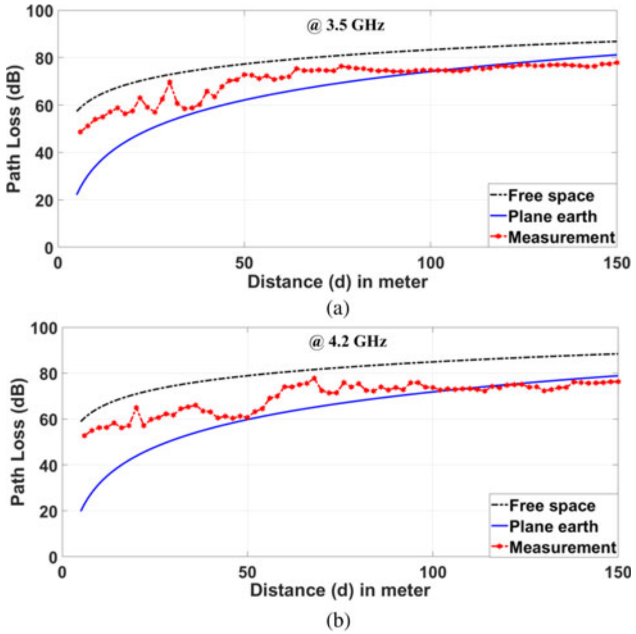
$$PL_{free\text{-}space}(\text{dB}) = -27.56 + 20\log_{10}(f) + 20\log_{10}(d) \tag{8}$$

where f is the frequency in GHz and d is the distance between transmitter and receiver in meters.

The near-ground propagation model is used for the scenario where the height of the receiver (h_{rx}) and the transmitter (h_{tx}) are taken into consideration in the near-ground studies in forest areas. This model also known as a two-ray model is valid when h_{rx} and h_{tx} are less than the distance ($h_{tx} \ll d$). The path loss model for plane-earth is given in (9).

$$PL_{plane-earth} = 40\log_{10}(d) - 20\log_{10}(h_{tx}) - 20\log_{10}(h_{rx}) \tag{9}$$

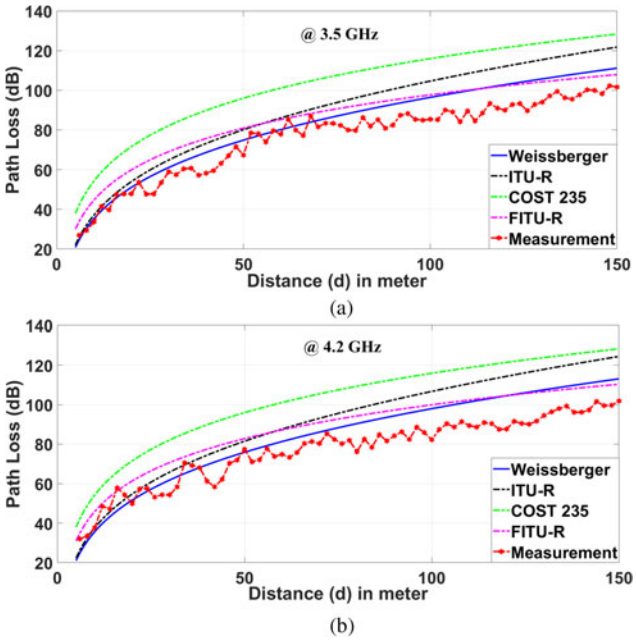
The plane-earth measurements are conducted on a grassy ground where no obstruction exists on LOS between transmitter and receiver antenna in Fig. 3. It should be noted that the antennas are placed at 2 m of height. The simulated results of free-space and plane-earth models according to (8) and (9), and the measured results for 3.5 and 4.2 GHz are given in Fig. 3. They are conducted in three different locations with similar features in this



(a)

(b)

Fig. 3. Simulated results of free-space and plane-earth models and the measured results (a) at 3.5 GHz and (b) at 4.2 GHz.



(a)

(b)

Fig. 4. Comparison of empirical models and the measurement in the forest (a) at 3.5 GHz and (b) at 4.2 GHz.

region, and average values of these three measurement environments with pine trees are taken in Fig. 4.

The measurements are repeated three times at the same location to increase the accuracy and the results are plotted according to the average of these three values. Accordingly, the loss in free-space in the entire frequency region is higher than the loss in the plane-earth environment because, for the plane-earth, the EM wave goes to the receiver both directly and by reflecting from the plane. While the measurement results remain between free-space and plane-earth up to 100 m, it proceeds around the plane-earth model between 100–150 m. At a distance greater than ~75 m, the path loss becomes almost stable.

Total path loss in the forest areas is expressed as.

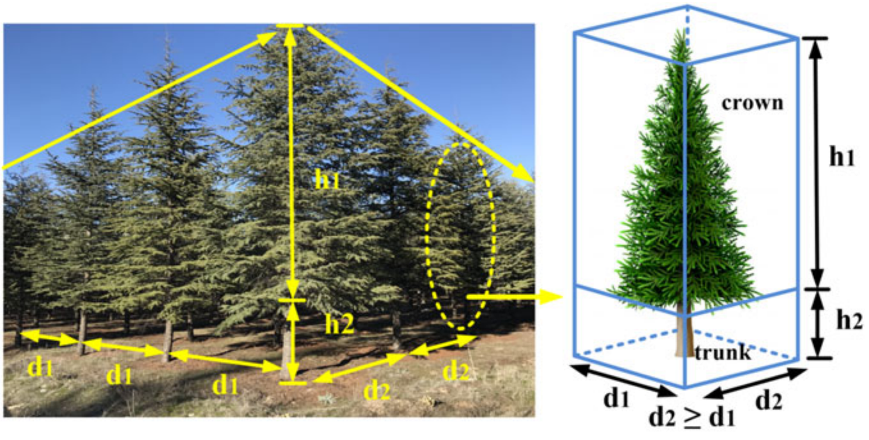
$$PL_{forest} = PL_{plane\text{-}earth} + PL_{veg} \tag{10}$$

where PL_{veg} is the vegetation path loss in dB. The comparison of empirical models and the measurements for 3.5 and 4.2 GHz are given in Fig. 4. The path loss of plane-earth in Fig. 3 according to (9) and the foliage path loss in Fig. 4 are measured to generate the model. Since the lateral wave effect is out of the aim of this study, the LITU-R model is not calculated and shown. According to Fig. 4, while the measurement results are closer to the results of the Weissberger and FITU-R models, they are far away from the results of the COST235 and ITU-R models since COST235 and ITU-R models are obtained from measurements made in humid and temperate climates. In general, path loss increases by increasing distance and frequency in all models. It is determined that the measurement results differ from other models as the distance increases. A similar situation exists among other models where formulations are seen in [2–6].

Measurement environment near Golcuk Lake and the dimensions of identical trees with trunk and crown are given in Fig. 5. In order to predict the effect of v in the forest area on the path loss model more accurately, it is significant that the trees have the same height and width as given in Fig. 5. The average height and width of trees are 8 and 4 m, respectively. The distance between the trees is 4 and 6.5 m for reference measurement to determine v on the model.

The measurement results show that the path loss increases with the rise of v. Different distances d_1 and d_2 are taken into account and the reference measurement is also repeated three times for each distance. In general, v is a parameter that depends on not only the height and diameter of the crown but also the height and diameter of the trunk tree. EM waves propagated from the transmitter reach the receiver not only directly but also by multipath due to the reflection and scattering effects. Accordingly, it is determined that the dimension of the crown and trunk of all trees between the receiver and the transmitter affects path loss. The ratio of the unit rectangular prism volume to a single tree volume is calculated to obtain v as in Fig. 5(b). Volume of a tree in (11) is found by the sum of the volumes of the trunk and crown of the tree. Equations (11a) and (11b) give roughly tree crown and trunk volumes, respectively. Accordingly, trunk and crown volumes are calculated with cylinder and cone volume formulas, respectively.

$$V_{tree} = V_{trunk} + V_{crown} \tag{11}$$



(a)

(b)

Fig. 5. (a) Measurement environment in Golcuk and (b) the dimensions of identical trees with trunk and crown.

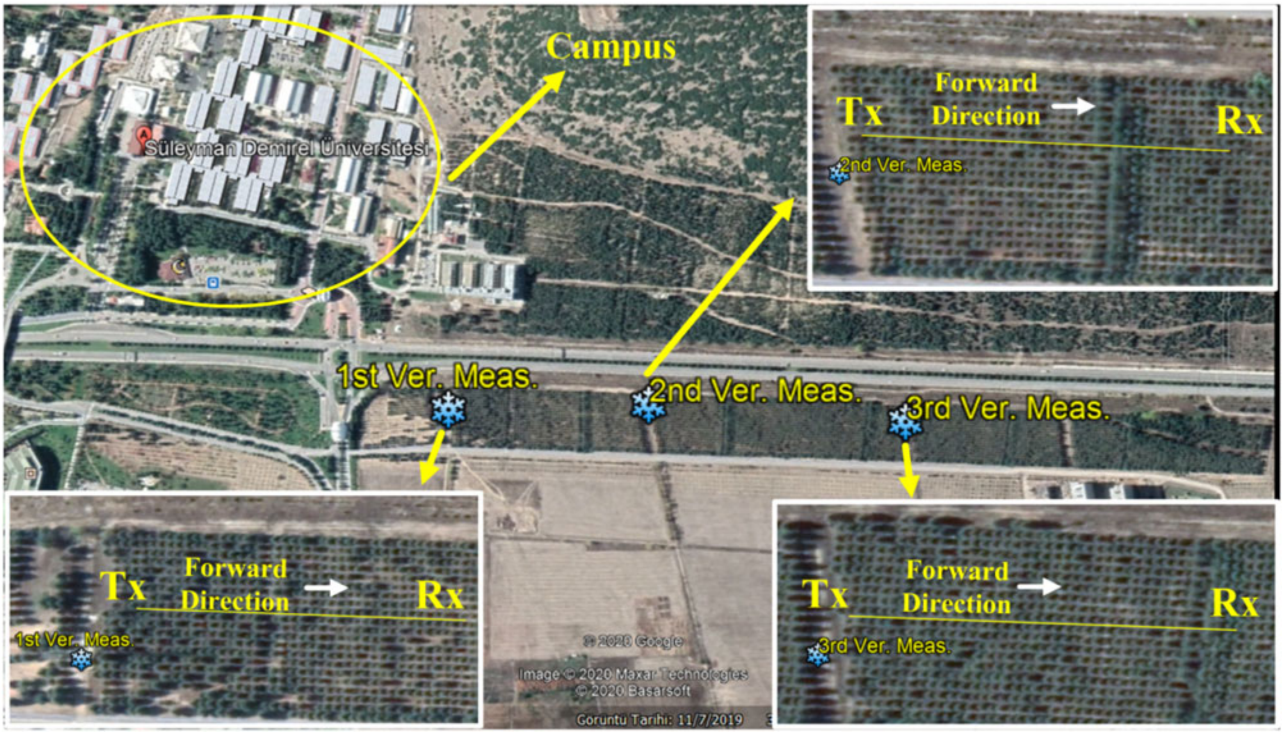


Fig. 6. Measurement region to verify the generated path loss model.

$$V_{crown} = \frac{\pi r_c^2 h_1}{3} \tag{11a}$$

$$V_{trunk} = \pi r_t^2 h_2 \tag{11b}$$

$$V_{tree} = \pi r_t^2 h_2 + \frac{\pi r_c^2 h_1}{3} \tag{11c}$$

while r_t and r_c are the radii of the trunk and crown base, respectively, h_1 and h_2 are the heights of the trunk and crown, respectively. Also, the volume of the rectangular prism containing a single tree as in Fig. 5(b) is given as

$$V_{prism} = d_1 d_2 (h_1 + h_2) \tag{12}$$

where d_1 and d_2 are the distances between two trees on the x- and y-axis, respectively. Therefore, v is found as the ratio of the total volume of the tree to the volume of the rectangular prism as

$$v_{ref} = \frac{V_{tree}}{V_{prism}} = \frac{\pi r_t^2 h_2 + (\pi r_c^2 h_1\ /3)}{d_1^2 (h_1 + h_2)} \tag{13}$$

where v_{ref} is the reference volumetric occupancy rate. In the first reference measurement, $d_1 = d_2 = 4$ m. While r_t and r_c are the radius of the trunk and crown, respectively, h_t and h_c are the height of the trunk and crown, respectively. It is observed that $r_t = 15$ cm, $r_c = 3$ m, $h_1 = 3$ m, $h_2 = 10$ m. Additionally, v_{ex} is the examined volumetric occupancy rate. In the second reference measurements, while h_1 and h_2 are the same according to the first case, $d_1 = 4$ m and $d_2 = 6.5$ m.

$$v_{ex} = \frac{V_{tree}}{V_{prism2}} = \frac{\pi r_t^2 h_2 + (\pi r_c^2 h_1\ /3)}{d_1 d_2 (h_1 + h_2)} \tag{14}$$

where v_{prism2} is the rectangular prism volume in the examined environment. v is obtained by dividing the v_{ref} by the v_{ex}. This parameter is non-dimensional and ranges between $0 < v \leq 1$.

$$v = \frac{v_{ref}}{v_{ex}} \tag{15}$$

The proposed model is generated based on three different parameters as in (16). Using the measurement data at the three different frequencies mentioned above, it is determined that the model changes depend on the function $f^{0.28}$.

$$PL_f(\mathrm{dB}) = v\ L_{veg}(d)\ f^{0.28} \tag{16}$$

where L_{veg} is the distance-dependent vegetation loss factor and P_{Lf} is total path loss in the forest including foliage effect and the plane-earth. The proposed model is obtained using the curve fitting method in Matlab®. Curve Fitting Toolbox in Matlab is an easy-to-use application to create any function to fit curves and surfaces to data. This toolbox enables calculating ERMS and R-squared values automatically. Before curve fitting, the v coefficient in (16) for the measurement environment is calculated as 0.61. Also, the effect of the frequency on the path loss is determined using the measurement results made at different frequencies and thus the exponent of the frequency is calculated as 0.28 in (16). After determining v and the exponent of the frequency, the model consists of a distance-dependent function. Firstly, this toolbox can be opened with the command called *cftool* at the Matlab

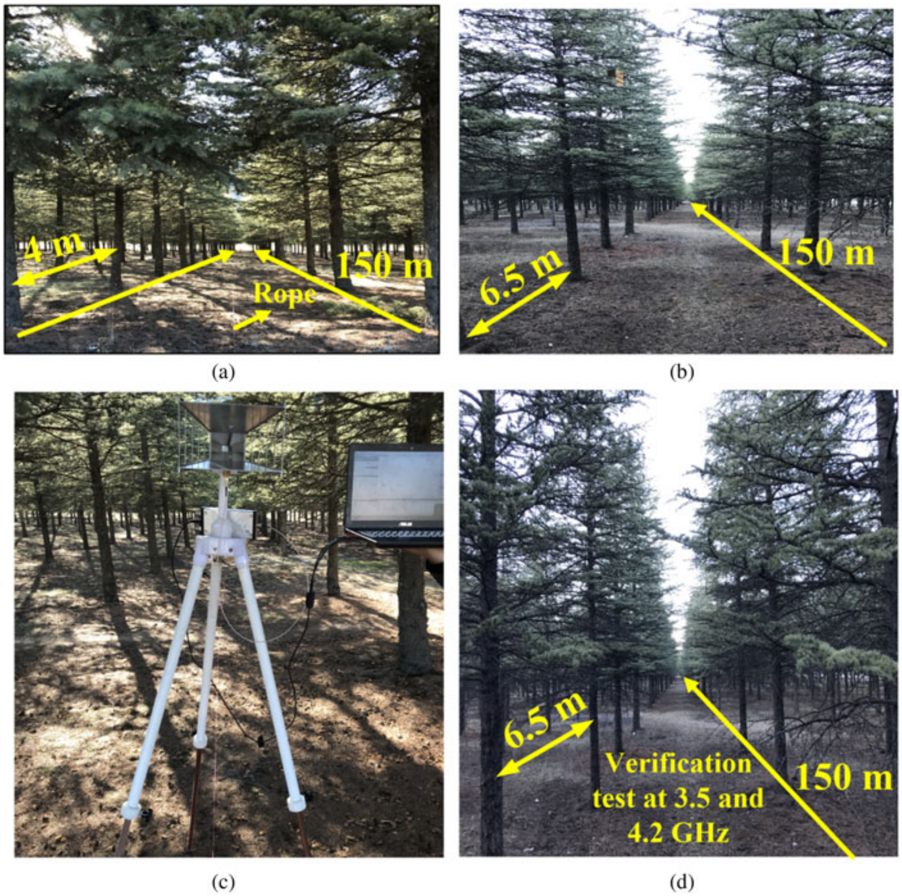


Fig. 7. Reference and verification measurement environments for 3.5 and 4.2 GHz.

prompt. At its interface, while the distance data are imported as X data, the result of reference measurement for each frequency is imported as Y data. Then, any function type at the interface can be added for curve fitting. However, to have more accuracy of the model, L_{veg} is determined as a two-term exponential function containing four different constant coefficients to obtain best-fit parameters in (17). Even if the function type of the model can be considered as a polynomial (quadratic or cubic) or force function, it is expressed as the exponential function since the error is less [the root mean square error (RMSE) value is very close to 1]. These coefficients are found as $x = 83.51$, $y = 0.002$, $z = -64.91$, and $t = -0.034$. This model is valid where vegetation area is covered by equidistant, identical trees.

$$L_{veg}(d) = x\ e^{(yd)} + z\ e^{(td)} \tag{17}$$

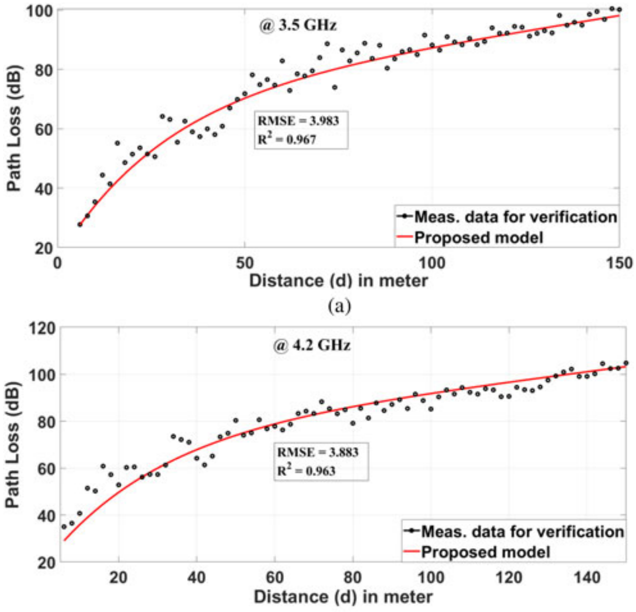
As aforementioned, the proposed model depends on distance, frequency, and v. The path loss value increases by increasing distance and frequency. Since the measurements are made between 5 and 150 m, the model does not work properly at distances more than 150 m. According to the measurement results, the model can be used in 1–7 GHz frequency ranges with a maximum error of ±4 dB. In this range, the error is about ±4 dB at frequencies close to the lower and upper limits, while it is less at the center of this frequency range. In addition, v coefficient depends on the dimension of the trunk and crown in the pine tree. As a result, the proposed model is valid for only pine forest and the height of trees varies between roughly 5 and 20 m.

The verification of the proposed model

To verify the proposed path loss model shown in Fig. 6, the region with pine trees located in Süleyman Demirel University Campus, which is a different region from Golcuk, is selected and verification measurements are carried out in three different areas of this region. It should be noted that the coordinates of this region are 37° 50′ 22.61″ N and 30° 31′ 42.01″ E. The ground is completely flat and the trees are in a straight line. More than one measurement results are evaluated both to generate the model and to verify this model.

All measurement environments for two different frequencies are given in Fig. 7. Figures 7(a) and 7(b) show the reference measurements in the Golcuk to generate model at 3.5 and 4.2 GHz. The distances between trees in Figs 7(a) and 7(b) are 4 and 6.5 m, respectively. Figure 7(d) includes verification measurements made to verify the generated model on the Campus at the same frequency. The distance between trees is 6.5 m and the total measurement length is 150 m. Since the measurement interval is 1 m, there are 150 different points in the test region. In the verification measurement, $d_1 = 4$ m and $d_2 = 6.5$ m. While r_t and r_c are the radii of the trunk and crown, respectively, h_t and h_c are the heights of the trunk and crown, respectively. It is observed that $r_t = 10$ cm, $r_c = 2$ m, $h_1 = 1.75$ m, $h_2 = 7$ m. Figure 7(c) shows the measurement test-setup. The verification measurements are made at both 3.5 and 4.2 GHz. It should be noted that v is nearly 0.61 for both reference and verification test regions.

To verify the performance of the proposed model, the measurement results, and the proposed model at 3.5 and 4.2 GHz



(a)

(b)

Fig. 8. Measurement data for verification and the proposed model at (a) 3.5 GHz and (b) 4.2 GHz.

are given in Fig. 8. *R*-squared value between the measurement and the model for the first frequency is calculated as 0.967 and its accuracy is at an acceptable level. RMSE value between them is calculated as 3.983. Then, the performance of this model is compared with the performance of other models in Table 1. For 4.2 GHz, *R*-squared and RMSE values are also obtained as 0.963 and 3.883, respectively.

After the verification, the effect of v on the performance is depicted in Fig. 9. Accordingly, it is seen that v has a significant effect on model performance. According to (15), v is equal to 0.615. As seen in Fig. 9, the result of verification measurement and the result of the proposed method with 0.6 of v agree with each other.

The results and model performance

The concept of error in the measurement is defined as the difference between the measured and calculated values. To evaluate the model performance, various common metrics such as the mean absolute error, the mean squared error, mean absolute percentage error, and RMSE can be used. However, the RMS method is the most commonly used performance metric in the literature to evaluate the model performance. RMS errors (E_{rms}) for proposed model and other empirical models such as Weissberger, ITU-R, Kurnaz and Helhel [3], and Chen and Kuo [27] models can be defined as

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{n} (E_p - E_m)^2}{n}} \tag{18}$$

where n is the number of measurement points, E_p is value from the proposed model or the values from other empirical models, and E_m is the measured value at ith measurement point in dB.

The comparison of the proposed model and other empirical models for 3.5 and 4.2 GHz is given in Fig. 10. Accordingly, the closest model among empirical models to the proposed model is Kurnaz and Helhel model in 3.5 GHz, while it is Chen and Kuo model in 4.2 GHz. It is observed that the results of the proposed one and the Chen and Kuo models overlap in the range of 5–70 m. It is determined that the average path loss difference of the models between the two frequencies is 2.58 dB. ITU-R and Weissberger models overestimate the path loss when the foliage depth is increased. This can be caused by two possible reasons. The first reason is that these two models are generated into the environment with very dense foliage density in the forest, unlike the other models. The second one is that these two models have only better performance at frequencies lower than those measured in this study.

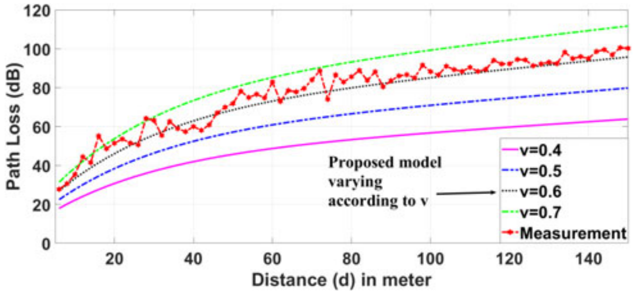
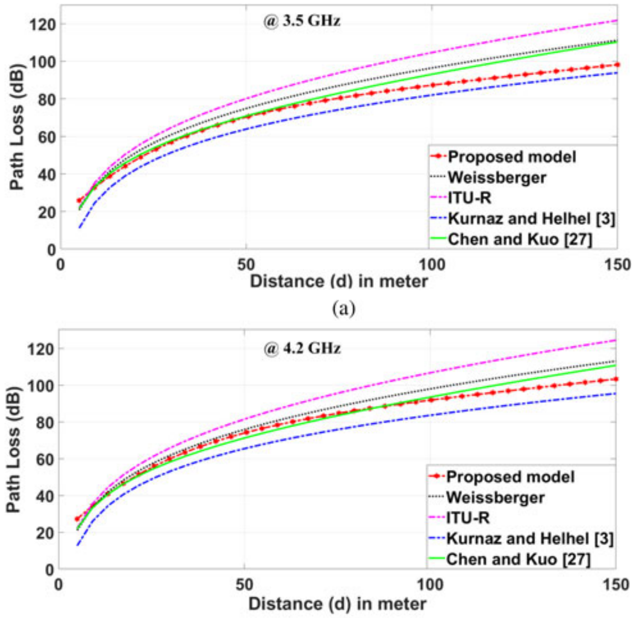


Fig. 9. Effect of v on the performance of the proposed model.



(a)

(b)

Fig. 10. Comparison of the proposed model and other empirical models (a) at 3.5 GHz and (b) 4.2 GHz.

RMS errors and *R*-squared values between models and verification measurements are given in Table 2. The results of verification measurement specified before are obtained between 5 and 150 m. According to the table, the model with the highest RMS error with our proposed model is the ITU-R model for both frequency values. Also, Weisberger and ITU-R models are not suitable for pine forests with different foliage densities because the error is higher than the expected one. Since in the Kurnaz and Helhel and Chen and Kuo models, k (the ratio of heights of the trunk of the tree) in [3] and n (exponent constant depending

Table 2. RMS errors and R-squared values between the models and verification measurements.

	The proposed model	Weissberger model	ITU-R model	Kurnaz and Helhel model	Chen and Kuo model
Frequency	E_{rms}	E_{rms}	E_{rms}	E_{rms}	E_{rms}
3.5 GHz	3.98 dB	8.08 dB	15.20 dB	5.84 dB	5.87 dB
4.2 GHz	3.88 dB	5.51 dB	13.01 dB	8.14 dB	4.31 dB
Frequency	R-squared	R-squared	R-squared	R-squared	R-squared
3.5 GHz	0.967	0.952	0.939	0.957	0.956
4.2 GHz	0.963	0.958	0.942	0.951	0.963

on the foliage density) in [27] variables vary depending on the foliage density in the forest, these two models can be used in different environments. Since the v parameter includes the distance between trees, the dimensions of the trunk, and the crown, the proposed model has more accuracy and is more comprehensive than other models. Therefore, it gives better results compared to other models in different frequencies and various forest areas.

Conclusion

In the LOS scenario where there is no obstacle between the transceiver, EM wave propagated from the transmitter reaches the receiver directly. For the forest area, in the absence of some obstacles as considered NLOS, there are various dominant propagation modes such as multipath reflections, diffraction, scattering, and/or refraction. These modes due to the trees, trunks, leaves, and so on create an NLOS path. In this paper, the new empirical path loss model based on the frequency, distance, and the volumetric occupancy rate is proposed at the 3.5 and 4.2 GHz in the scope of 5G frequency bands. This study is focused to determine the effect of v on path loss depending on the foliage density. The artificial forest area consists of regularly sorted and identical pine trees. The results of the proposed model are compared with four different path loss models and average E_{rms} at 3.5 GHz occur as 3.98, 8.08, 15.20, 5.84, and 5.87 dB for the proposed model, Weissberger, ITU-R, Kurnaz and Helhel, Chen and Kuo models, respectively. Therefore, the proposed model gives better performance than other models.

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