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Path Loss Prediction Model Development in a Mountainous Forest Environment

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ABSTRACT We consider a method for developing a radio-wave propagation prediction model in a mountainous forested area. A new path loss development approach uses a free-space path loss (FSPL) model and an empirical path loss model. To improve the prediction accuracy, the transmission path distance, free space area, and forest area were calculated separately. We obtained the transmission path distance for free space and forest areas from the digital surface model (DSM), which represents surface elevation information, including vegetation and object height. In this study, the results showed that by combining the empirical model with FSPL for free space area, the accuracy for all the empirical models was improved. We confirmed that the transmission distance calculation of the free space area and forest area with a combination of the empirical models showed a better performance than the model with physical distance. The predicted model results were validated using the actual radio wave propagation in the 920 MHz band measurement data. The overall path loss prediction accuracy was improved for the empirical models average of 8.05 dB on the experimental data.

INDEX TERMS Digital surface model, LoRa, path loss prediction, modified empirical model, drone mapper.

I. INTRODUCTION

RADIO-WAVE propagation modeling is a fundamental study in wireless communication technology. Since the first radio transmission of Guglielmo Marconi in 1901, radio wave propagation characteristics have been studied extensively in the development of wireless communication around the world [1]. Radio propagation environments have been widely divided into rural, suburban, and urban areas [2]. Depending on the transmission environment, the obstacles cause the radio wave to be reflected, refracted, diffracted, scattered, or blocked. The path-loss model represents the signal power loss when it propagates from the transmitter to the receiver. Since the 1960s, numerous studies have been conducted to investigate the actual radio wave propagation characteristics in forest environments. Traditionally, path loss propagation models in forested environments can be divided into two categories: analytical radio propagation prediction and empirical radio propagation prediction. Analytical models were developed based on the physical characteristics of radio wave propagation. Physics-based analytical models require knowledge of the physical laws of the radio wave, the ability to use mathematical calculations, and heavy computational resources. Empirical models can be developed easily based on the measurement of attenuation data. The main advantage of the empirical model is its simplicity and applicability for any experimental area compared to the analytical model [3].

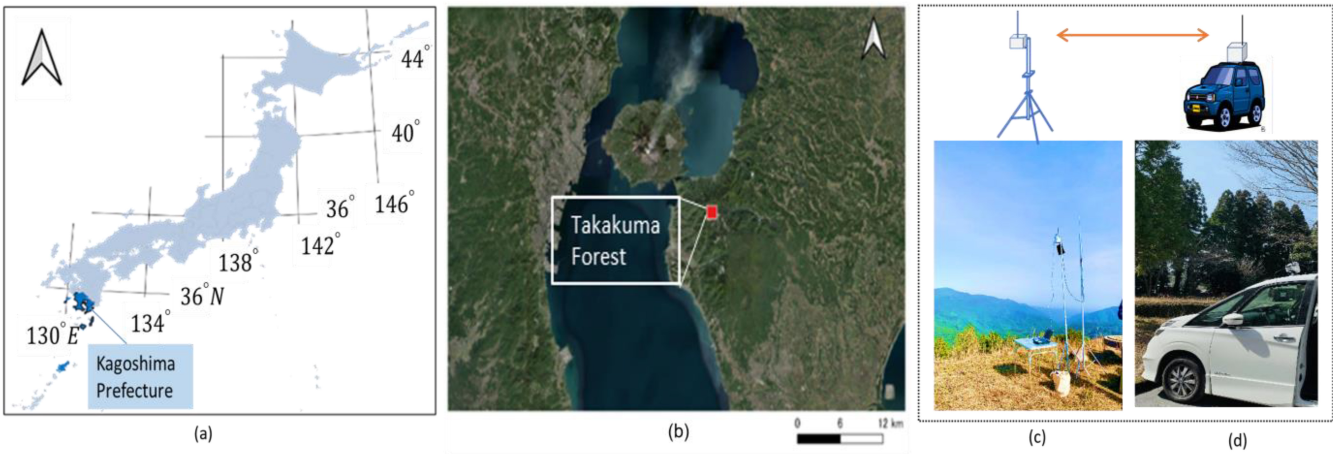

FIGURE 1. Experimental setup: (a) Map of Japan; (b) Experimental area; (c) receiver antenna located at Mt. Takatouge; (d) transmitter antenna mounted on the roof of vehicle.

The most popular empirical path loss model in forests was proposed by Weissberger [4] in 1982. The empirical models were developed based on the experimental data COST235 [5], ITU-R [6], FITU-R [7], and lateral ITU-R [8]. They were applied to fit the data based on the experiments where each parameter had different values of the determined parameters [4]–[8]. Empirical models based on regression methods are commonly used to estimate propagation based on the type of vegetation environment [9]–[11]. Radio-wave propagation characteristics in forest environments can be divided into direct, reflected, and lateral waves [12]. The direct and reflected waves propagate through the forest, and the lateral waves propagate through the tree crowns over the top of the vegetation. The models were developed for the situation where antennas are both located inside the forest near the grove of trees and the signal propagates mainly through the trees. Therefore, existing empirical models in forest areas have specific advantages and disadvantages and do not apply to every propagation environment.

However, many empirical models have been developed in the measured environment, but they fail when applied to different measurement environments and experimental setups for which it was developed [13].

Modified empirical models in forest environments were evaluated and developed in [18], [19], and [20].

The reliability of the network access depends on the accuracy of the propagation model performance. Hence, the need for a simple and realistic prediction of the empirical model's improvement in the prediction accuracy is maintained.

The main objective of this research is to develop a simple and accurate model based on the combination of an empirical path loss model and a free-space path loss (FSPL) model to improve the overall prediction accuracy in a forested environment. We proposed a model in which the total signal path loss between the transmitter and receiver is divided into two parts: free space loss and forested space loss. In addition, the proposed model was evaluated using field experiment data. The experiment was conducted in Kagoshima University Forest, which is the 5^{th} largest university forest. There are 27 universities with a university forest in Japan. The university forest is a large classroom for students [22]. Focusing on Japan's forestry, most of the forests are in the mountains. There are many places where radio waves do not reach due to the influence of forest and terrain [23].

To establish a reliable communication network for forest ICT and inside of the forest there are no signal for the cellphone therefore safety of the workers and students in the forest, we need a precise path loss prediction model that is suitable for this laurel forest environment.

II. MATERIAL AND METHODS

A. EXPERIMENTAL SETUP

The field experiment was conducted in February 2020 at Takakuma Experimental Forest (31.5° N, 130.7° E) of Kagoshima University, Tarumizu City, Kagoshima Prefecture, southern Japan. The dominant tree species were the Japanese cedar and Japanese cypress. The details of the measurement setup are shown in Figure 1. A map of Japan is shown in Figure 1(a), where the dark blue colored area is the Kagoshima prefecture; in Figure 1(b), the red rectangle is the location of the experimental area in this study. In this study we used low-cost broadcast-based location information sharing system called Drone Mapper using 920 MHz.

Drone Mapper system is based on simple device-to-device (D2D) broadcasting protocol can establish the communication network that not requiring the infrastructure or access point [25]. The purpose of this system is location information sharing between unmanned aircrafts (UA) and their operators or between the flying vehicle to ensure their safe operation. Drone mapper system collect the information name of the vehicle, time, latitude, longitude, altitude, speed, direction, and the signal strength [24], [25], and [26].

The two Drone Mapper units (the receiver and the transmitter) were deployed in this experiment. The experiment was conducted by installing a receiver antenna (Rx) at

TABLE 1. Experimental setup.

Description	value
Compliance technical standard	Specifications defined in EEE802.15.8, ARIB STD T108 Specific low power radio station
Rx Height (above ground)	2.5 m
Tx Height (above ground)	2 m
Transmission power	13 dBm
Antenna Gain (dB)	0
Spreading factor (sf)	12
Frequency	920 MHz
Wireless channel bandwidth	400 kHz
Modulation method and data rate	2-FSK/LoRa, 200 kbps/20kbps (Gp:7) (duty rate 360 sec/hour or less)
Reception sensitivity	2-FSKTyp. - 98 dBm (BER 0.001), LoRa Typ. -131 dBm (BER 0.001)
Antenna directivity	Vertically polarized wave, monopole antenna

TABLE 2. Parameter values for empirical model.

Model name	A	B	C	Frequency
Weissberger [4]	1.33	0.284	0.588	230 MHz to 95 GHz
ITU-R [6]	0.2	0.3	0.6	200 MHz to 95 GHz
COST235 [5]	15.6	-0.009	0.26	9.6 to 57.6 GHz
FITU-R [7]	0.39	0.39	0.25	11.2 and 20 GHz
Lateral ITU-R [8]	0.48	0.43	0.13	240 and 700 MHz

the summit of Mt. Takatouge (722 m high), as shown in Figure 1(c). The height of the receiver antenna is approximately 2.5 m above ground. The transmitter car ran through the inside of the experimental forest and transmit the signal collected at the receiver antenna. Figure 1 (d) shows a transmitter antenna (Tx) mounted on the roof of a vehicle approximately 2 m above the ground with a 13 dBm transmitter power. It has an antenna gain of 0 dB. Long Range (LoRa) communication technology is used in this study. The specifications of the experimental setup are listed in Table 1. Both the receiver (Rx) and the transmitter (Tx) had a whip-type antenna (horizontal surface omnidirectional). The measured data include the received signal strength indicator (RSSI), altitude of the transmitter antenna, and geographical coordinates.

B. OVERVIEW OF RADIO WAVE PROPAGATION MODEL

The empirical path loss model was developed based on the experimental data, accounting for the effect on vegetation. Each model uses a specific parameter for prediction with good accuracy. The empirical path loss model provides a method for modeling path loss data in each range of measured data, but each path loss model has advantages and disadvantages. Each model has limitations that depend on the propagation environment and experimental setup, which are unable to model the path loss. To model path loss in a mixed forest, Tx-Rx as distance is considered. We propose a path loss model combining the FSPL model using the distance of a free space area and an empirical path loss model for forest areas.

Free Space Path Loss model: The FSPL model is the theoretical data that predicts radio wave propagation path loss in free space without obstructing objects over a distance. This model considers only the frequency and the propagation distance and does not consider radio wave propagation effects, such as reflection, refraction, diffraction, and absorption. Path loss expresses the loss in signal strength as a function of the distance.

The FSPL model can be calculated as follows:

$$L_{fspl}(db) = 20 \log 10(4\pi d/\lambda), \tag{1}$$

where L_{fspl} is the free space path loss in dB, d is the distance between the receiver and transmitter antenna in meters, and λ is the wavelength in meters.

Link budget: The link budget calculates the total received signal strength in dBm, accounting for all gains and losses in a transmission system. The link budget can be calculated as follows:

$$P_r\ (dbm) = P_t + G_r + G_t - L, \tag{2}$$

where Pr is the received power expressed in dBm, Pt is the transmitter power in dBm, Gr is the receiver antenna gain in dB, and Gt is the transmitter antenna gain in dB.

Empirical Path Loss Model in Forest: The exponential decay approach to modeling path loss in vegetation, which assumes that the loss increases exponentially with distance, was first proposed by Weissberger [4] in 1982. The modified version of the model was included in the International Radio Consultative Committee Recommendations (CCIR) in 1986 [5].

In this study, five well-known empirical path loss models for vegetation, namely, Weissberger's [4] modified exponential decay model, ITU Recommendation (ITU-R) [5], COST235 [6], FITU-R [7], and lateral ITU-R [9] are developed. The modified exponential decay (MED) path loss models A, B, and C parameter values can be empirically determined. The A value is determined based on the foliage type, and the B and C values represent the frequency and distance dependencies, respectively. Models A, B, and C are estimated from the experimental data, and depending on the experimental data, each parameter value of the fitted parameters is different. In this study, for all models, only the in-leaf foliage models were used in our experimental site. In Table 2, all empirical models used in this study are summarized.

The MED model can be calculated as:

$$L_{MED}(dB) = Af^B d^C, \tag{3}$$

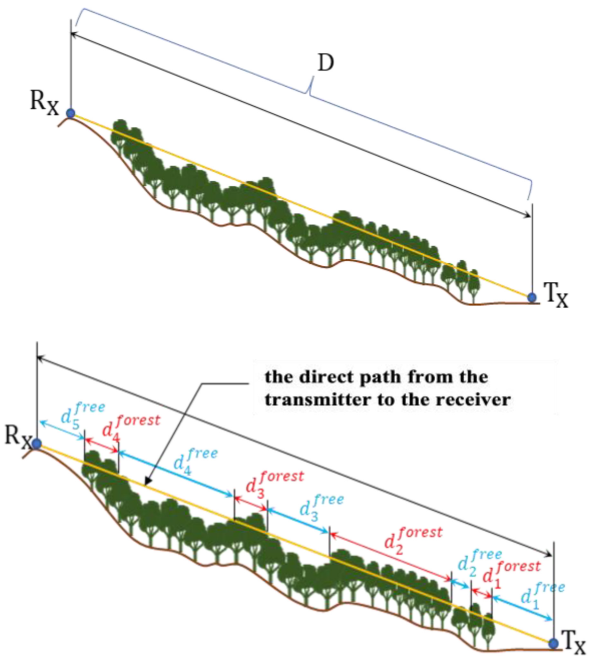

FIGURE 2. Illustration of the direct path, the transmission path distance for the forest area and for the free space area in the proposal methodology.

where the parameters A, B, and C are fitted values, f is the frequency, and d is the distance between the transmitter and the receiver.

Weissberger's model was developed under the situation where both antennas were located in the ground with a foliage depth of 400 m and a frequency range of 230 MHz to 95 GHz. The ITU-R model was developed at a frequency of 200 MHz and 95 GHz, and both antennas were located near a tree grove. The COST 235 model was proposed at millimeter frequencies from 9.6 GHz to 57.6 GHz and the antennas were located near a tree grove. The Fitted ITU-R (FITU-R) model was proposed at frequencies of 11.2 GHz and 20 GHz. The lateral ITU-R (LITU-R) model was proposed at frequencies of 240 MHz and 700 MHz, and the model considering the lateral wave effect.

C. PROPOSED PATH LOSS MODEL

The proposed path loss model is obtained by combining the FSPL path distance for the free area and empirical models using distance for the forest area. In Fig. 2, the illustration of the proposed path loss model shows the transmission distance from Tx to Rx (a), transmission path distance for the forest (b), and free space area (c). The definitions of variables are presented in Table 3.

When transmitting the signal between the transmitter and the receiver, the propagation path can be divided into direct line-of-sight paths and indirect non-line-of-sight paths. The direct line-of-sight path corresponds to the free space area between the transmitter (Tx) and receiver (Rx). The indirect non-line-of-sight path corresponds to the forest area propagation path by physical objects (such as buildings, terrain, or trees), and could affect the level of the signal or block

TABLE 3. Glossary of variables and parameters.

Symbol	Description	Unit
D	total transmission path distance between the transmitter and the receiver	m
D_{forest}	total transmission path distance for the forest area	m
D_{free}	transmission path distance for the free area	m
L_{fspl}	free space path loss	dB
P_r	received power	dBm
P_{fspl}	path loss for the free space area (distance for the free area)	dBm
L_{MED}	empirical path loss model (total transmission path distance)	dBm
P_{MED}	path loss for the forest area (distance for forest area)	dBm
$P_{proposal}$	combination of an path loss for the forest area and path loss for the free space area	dBm
MAD	Mean absolute difference	dB

the signal. Our proposed model considers the transmission path distance separately for free space and forest areas using digital surface model (DSM) data.

Proposed path loss prediction model for this study can be calculated using the following equations from (4)-(9). In the model the total transmission path distance between the transmitter and the receiver, D is divided into two parts, the total transmission path distance for forest areas D_{forest}, and the total transmission path distance for free space areas D_{free}.

$$D = D_{forest} + D_{free}, \tag{4}$$

where D is the total transmission path distance between the transmitter and the receiver in m, D_{forest} is the total transmission path distance for the forest area in m, and D_{free} is the transmission path distance for the free area.

The D_{forest} and D_{free} are calculated using the equation (5) and (6).

$$D_{forest} = \sum_{i}^{n} d_i^{forest} \tag{5}$$

$$D_{free} = \sum_{j}^{m} d_j^{free} \tag{6}$$

The d_i^{forest} and the d_j^{free} are the i-th and j-th transmission path distance for a forest area and a free space area respectively.

$$P_{fspl} = P_t + G_r + G_t - L_{fspl}, \tag{7}$$

Here, P_{fspl} is the received power expressed in dBm, Pt is the transmitter power in dBm, Gr is the receiver antenna gain in dB, Gt is the transmitter antenna gain in dB, and L_{fspl} is the free space path loss in dB.

$$P_{MED} = P_t + G_r + G_t - L_{MED}, \tag{8}$$

where P_{MED} is the received power expressed in dBm, Pt is the transmitter power in dBm, Gr is the receiver antenna gain in dB, Gt is the transmitter antenna gain in dB, and L_{MED} is the path loss through vegetation in dB.

$$P_{proposal} = P_{fspr}\left(D_{free}\right) + P_{MED}\left(D_{forest}\right), \tag{9}$$

Here, $P_{proposal}$ is the received power expressed in dBm, P_{fspl} is the path loss for the free space area, and P_{MED} is the path loss for the forest area in dB.

D. DSM BASED OBSTACLE DETECTION IN THE TRANSMISSION PATH

In this study, we obtained the transmission distance for the free space area and the forest area using a DSM. The DSM represents surface elevation information, including vegetation and object height. Specifically, all trees and terrain height between the transmission paths were represented in a 3-dimensional (3D) database (DSM), which allowed forest area identification in the transmission path using a simple spatial analysis method of the profile. A DSM data resolution of 30 m can be freely downloaded from the JAXA ALOS Global Digital Surface Model website [21].

The surface profiles were generated using the geographic coordinates of the transmitter (Tx) and receiver (Rx) antenna locations. If the profile height values are below the fitting line, they are considered the transmission path for the free area, and if they are above the fitting line values, they are considered for the forest area. Significant signal attenuation is expected above the fitting line of a DSM value in the forest area. This was repeated for all positions along the transmission path, and the transmission path distance was calculated.

E. EVALUATION OF THE PROPOSED MODEL

In this study, the mean absolute difference (MAD) is calculated to evaluate the proposed model's results. The difference between the observed and predicted path losses is evaluated based on the MAD, which was calculated as:

$$MAD = \frac{1}{n}\sum_{i=1}^{n}|x_i - \mu_i| \tag{10}$$

Here, x_i and μ_i are the values of the estimated and measured RSSI data, and n is the total amount of data.

III. RESULTS

In our experiment, we measured data from the transmitter car to the receiver antenna as well as the RSSI. The experimental environment was a mountainous forested area. The communication distance was up to 2000 m. The received RSSI plots are shown in Figure 3. The DSM map of the experimental area is shown in Figure 3 (b). The received RSSI values indicated by the colored dots and black dots represent the receiver antenna. The received RSSI ranged between −87 and −125 dBm at the receiver, as shown in Figure 3 (a). Communication loss occurred from 1.8 to 2 km because the transmitter car was running behind the hilly mountain with a height of 532 m.

Parameter determination for MED models: From parameters A, B, and C of the MED models, only parameter value "A" was empirically determined through the regression technique based on our experimental data. In Table 4, the parameter values of Weissberger, ITU-R, COST 235, FITU-R, and lateral ITU-R values at this experimental site were determined to be 0.0022, 0.00014, 8.01, 0.0022, and 0.0021, respectively. However, some parameter (A) values were not significantly different between the original MED values and modified parameter values.

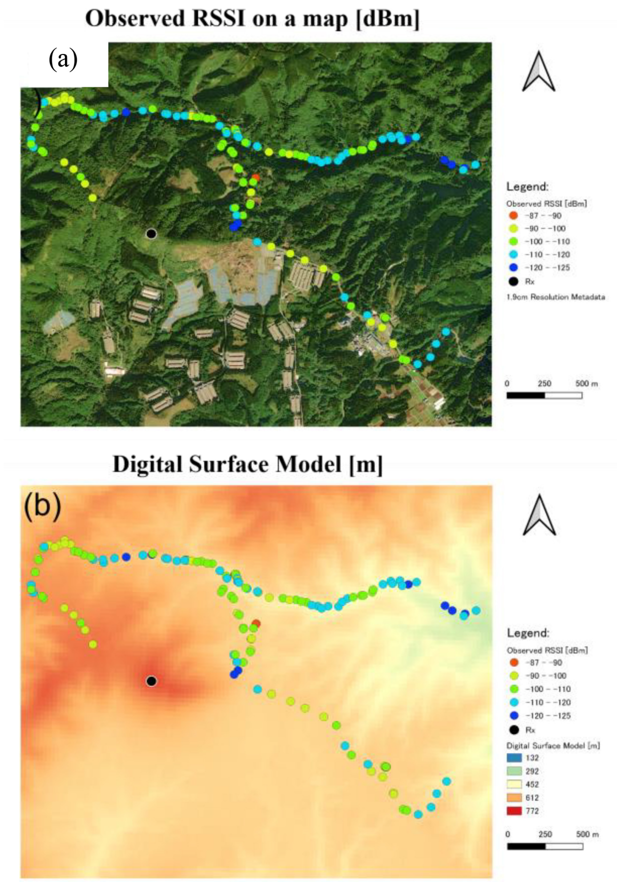

FIGURE 3. (a) Observed RSSI on a map. (b) Observed RSSI plotted on Digital Surface Map.

TABLE 4. MED Parameter value of A used for this study.

Model name	A (parameter value)
Weissberger	0.0022
ITU-R	0.0014
COST235	8.01
FITU-R	0.0022
Lateral ITU-R	0.0021

Figure 4 shows comparisons between the measurement data and predicted path loss using MED models with optimized A parameters using physical distance. The blue rectangle represents FSPL, light blue triangles represent COST235, yellow rectangles represent Weissberger, red rectangles represent ITU-R, purple rectangles represent lateral ITU-R, green dots represent FITU-R, and grey triangles represent experimental data. From Figure 4 in this experimental case, the Weissberger (yellow) and ITU-R (red) models could

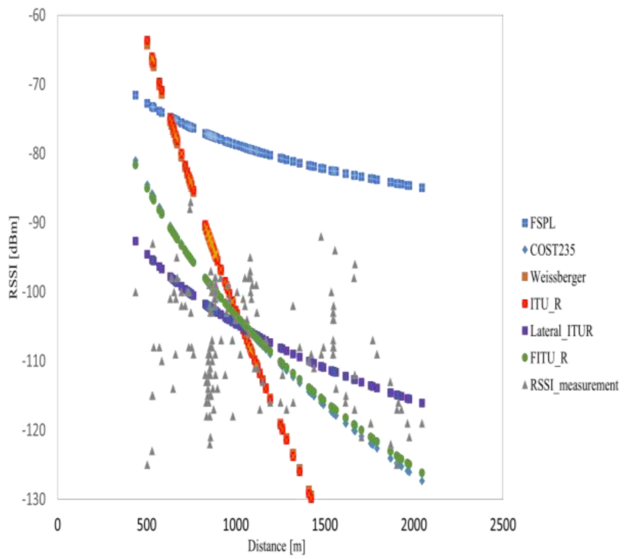

FIGURE 4. Comparisons between measurement data and predicted path loss using MED models with physical distance. Blue rectangle represents FSPL, light blue triangle is COST235, yellow rectangle is Weissberger, red rectangle is ITU-R, purple rectangle is Lateral ITU-R, green dot is FITU-R, and grey triangle is the experimental data.

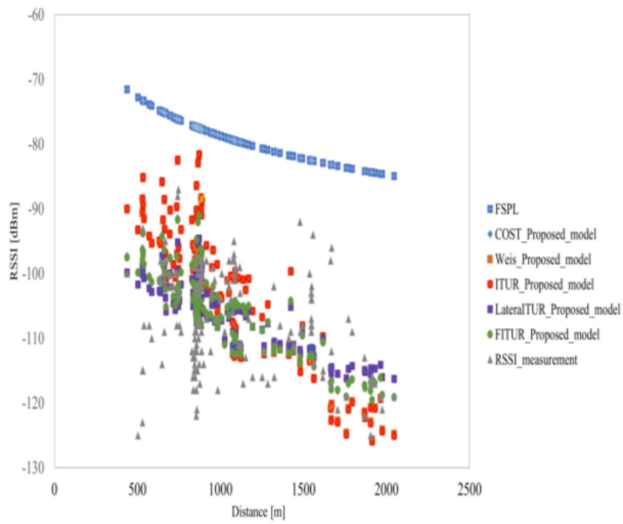

FIGURE 5. Comparisons between measurement data and proposed path loss using MED models with free space area. Blue rectangle represents FSPL, light blue triangle is COST235, yellow rectangle is Weissberger, red rectangle is ITU-R, purple rectangle is Lateral ITU-R, green dot is FITU-R, and grey triangle is the experimental data.

not predict the path loss distance of more than 1400 m. Thus, these models are unable to predict path loss over long distances. This is because the Weissberger and ITU-R models were developed based on a short (<400 m) forest depth with VHF and UHF bands. Therefore, these two models cannot be applied to large foliage depths. COST 235, lateral ITU-R, and FITU-R models are predicted distances of up to 2000 m. The COST 235 and FITU-R models showed similar predictions. This is because both models are derived from plan terrain with frequencies for COST 235 (9.6 and 57.6 GHz) and FITU-R (11.2 and 20 GHz).

Comparisons of the proposed path loss model results and measurement data are shown in Figure 5. The result of the proposed method Weissberger (yellow) and ITU-R (red) models predicted the path loss distance of more than 1400 m; in this case, these models were able to predict the path loss of up to 2000 m. COST 235, Lateral ITU-R, and FITU-R models well predicted a path loss distance of up to 2000 m. For the distance from 500 m to 900 m, the forest might be denser causing a decrease in received power measurement. Based on Figure 5, we observed that such matching makes the model more specific to a particular set of empirically gathered data and is less usable.

Table 5 shows the evaluation of the prediction model that used the original parameter with physical distance. Weissberger and COST 235 values of parameters were significantly lower than those of the original parameter in MAD (I) showing the evaluation of prediction path loss models that used the optimized parameter with physical distance. The MAD values of modified Weissberger, ITU-R, COST235, FITU-R, and Lateral ITU-R of values were 19.81, 20.23, 9.30, 9.04, and 6.72, respectively. MAD (II) shows the evaluation of the proposed path loss models of Weissberger, ITU-R, COST235, FITU-R, and Lateral ITU-R of values were 9.83, 9.94, 7.12, 7.04, and 6.32, respectively. By examining Table 5, the best performing model in this study is the Lateral ITU-R.

TABLE 5. Evaluation of the developed empirical model.

Model name	I (L_{MED})	II ($P_{proposal}$)
Weissberger	19.81	9.83
ITU-R	20.23	9.94
COST235	9.30	7.12
FITU-R	9.04	7.04
Lateral ITU-R	6.72	6.32

IV. DISCUSSION

In this study, the developed path loss models were compared with the experimental results. Figure 5 compares the empirical path loss model combined with FSPL models versus the experimental results in a forest area in Kagoshima. Our proposed path loss model provides all the empirical models with acceptable prediction accuracy for distances of up to 2000 m.

In Figure 4, the Weissberger and ITU-R models are unsuitable for predicting the radio wave path loss in this forest environment when the receiver antenna is above, and the transmitter antenna is under the forest trees. This is because these models were developed for different frequency bands than our experimental data. Furthermore, it might be that the majority of the signal propagates over the tree-top level; therefore, the lateral wave will contribute more, as reported in [16], and Li *et al.* [17], [18] propagation in forests. Therefore, the lateral ITU-R model matches well in both cases with our experimental data.

The MAD (I) values for the models (physical distance) calculated in comparison with the measured values are as follows: Weissberger (physical distance) MAD = 19.81 dB, ITU-R (physical distance) MAD = 20.23 dB, COST 235 (physical distance) MAD = 9.30 dB, FITU-R (physical distance) MAD = 9.04 dB, and Lateral ITU-R (physical distance) MAD = 6.72 dB.

In our proposed prediction of radio wave propagation in a mixed forest model, considering the transmission distance for free space and forest areas, the accuracy of the existing prediction model was successfully improved, making it applicable to other empirical models. As shown in Table 5, large differences exist between the path loss predicted by the empirical models combined with the FSPL and the empirical results. The comparison between the results of (FSPL + COST 235), (FSPL + FITU-R), and (FSPL + Lateral ITU-R) and the empirical measurements produced small MADs (7.12, 7.04, and 6.32, respectively). (FSPL + lateral ITU-R) has better results than the other models in a mixed forest. This is because the lateral ITU-R model was developed considering the lateral wave effect. Tamir noted that the lateral wave was dominant when the forest depth increased [18]. Therefore, the models do not predict well in the forest environment because they do not consider the lateral wave effect [19], [20].

However, the predicted path loss obtained from the models showed the worst case for MAD with the empirical ITU-R model of 20.23 dB, which decreased to the MAD of an estimated path loss of 9.94 dB. Therefore, the proposed path loss models provide better results than the other models.

When combining the parameter-optimized empirical model with FSPL and excluding the obstacle area from the calculation applied to all the empirical models in this study. Empirical models that exclude the forest from calculations could predict the path loss in such an environment. The results of the combined empirical model showed better performance than the parameter-optimized models.

V. CONCLUSION

In this study, we presented a method for the development of empirical path loss models based on the combination of an FSPL and an empirical path loss model, using the distance for free area obtained from a 3D site-specific model (DSM) in Kagoshima, Japan. We confirmed that the transmission distance calculation of the free space area and forest area with a combination of the empirical models showed a better performance than the model with physical distance. The predicted model results were validated using the actual radio wave propagation in the 920 MHz band measurement data. The overall path loss prediction accuracy was improved for the empirical models average of 8.05 dB on the experimental data. The results of this study showed that the lateral ITU-R path loss model is suitable for predicting the propagation loss in this scenario with a receiver antenna height of 2.5 m and the transmitter antenna moving inside the forest. The lateral ITU-R model was shown to have similar MAD values when using either the distance for the forest area or the physical distance, indicating slight to no difference between the two. This is because, in this scenario, the lateral wave effect might be dominant. The lateral ITU-R model was developed for leafy dense forests and considers the lateral wave effect.

Based on the empirical results, our proposed method is well suited for improving the applicability of all path loss models in a mountainous forested environment. Our proposed method could be used to develop a model for any reference distance, which may improve the practical application of the model. The prediction accuracy of the proposed model can be improved based on the transmission path calculation method and DSM data quality.

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