Excess Loss by Urban Building Shadowing and Empirical Slant Path Model

Youngkeun Yoon and Hyoung Jin Park

***Abstract*—Excess loss due to building shadowing is regarded as an obstacle effect by buildings existing on the radio propagation path in relation to the service coverage performance of the next-generation mobile communication. In order to overcome the limitations of a geometric or deterministic modeling of existing obstacle loss models (ITU-R, W-I, and W-B model) and increase the accuracy of prediction of excess loss below 10 GHz in real urban environments, the improved empirical model is proposed by adding new variable and optimized fitting parameter values to the existing ITU-R model's formula. New variable and optimized parameter values reflect complex building structure and building height and their propagation impact through measurement. For validation of the proposed model, the self-verification and cross-verification were performed using the measured data from Korea and Japan. The measured data as well as the proposed model were presented as root-mean-square error that can be compared with other existing models in accuracy. The new proposed empirical model showed good agreement with the measured data compared to the existing geometric and deterministic models. In conclusion, the proposed model can be applied to the slant path link below 10 GHz frequency.**

***Index Terms*—Clutter, deterministic, empirical, excess loss, slant path.**

I. Introduction

With next-generation mobile communication service, the interest and challenge for the high-speed and low-latency data transmission are increasing [1], [2]. The radio propagation prediction is required and continuously studied for considering path loss and excess loss related to the service coverage in urban environment [3]–[6]. Obstacles such as buildings in outdoor environment affect radio propagation path loss based on multipath or excess losses above rooftop path in the radio link [7]–[9]. Excess loss prediction due to obstacles in the earth-to-space path (slant path) link was described for modeling process in site-specific environment [10]. However, actual radio propagation environment contains the complex building or street tree structure and arrangement as well as around obstacles. Existing prediction models have the limitation as the geometric or deterministic simulation model not applied for actual complex rooftop and various material and diverse building structures. To overcome the disadvantage of the existing model based on site-specific modeling, the general excess loss model is developed based on the measurement in real urban environment. The existing ITU-R model [11] based on the ray tracing modeling method in the slant path link reflects the frequency and elevation angle effects in the 10–100 GHz frequency, not in the low frequencies. As the theoretical model only, a simplified clutter loss result and a curve fitting modeling method had been presented [12]. Clutter loss considering the elevation angle effect of 20° or less in microcell was derived from and based on the existing path loss value applicable to microcell and presented as a specific theoretical clutter loss model at single frequency. Therefore, the improved empirical model should be developed based on measurement for the slant path link in real environment. In this letter, excess loss measurement and modeling shadowed by the building for the slant path link are described. The proposed empirical excess loss model was verified based on the reliable measured data from Korea and Japan. The root-mean-square error performance was compared between models.

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The authors are with the Electronics and Telecommunications Research Institute, Daejeon 34129, Republic of Korea (e-mail: ykyoon@etri.re.kr; dlsn0515@etri.re.kr).

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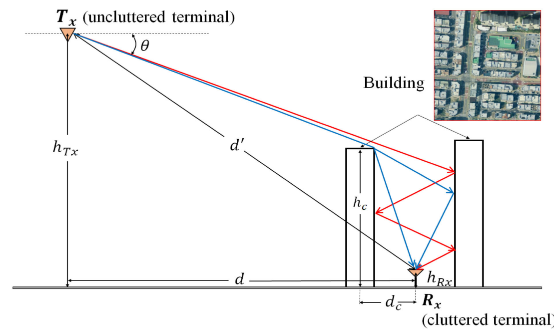

Fig. 1. Geometry description for fundamental excess loss.

II. Existing Prediction Model

A. Fundamental Excess Loss by Building Shadowing

Actually, excess loss can be described as clutter loss due to the difference between the presence and the absence of residential or commercial building (clutter) around radio propagation in urban environment. Excess loss is calculated by subtracting free-space path loss from transmission path loss between both terminals of the slant path link as shown in Fig. 1 [10], [11].

Excess loss, L_{CL} in dB, is given by

$$L_{CL}\ [\text{dB}] = L_{PL} - L_{FS} \tag{1}$$

where L_{PL} is transmission path loss based on the measurement data from Korea and Japan, and L_{FS} is free-space path loss.

Fig. 1 shows the description of excess loss by clutter shadowing geometrically. θ is the elevation angle in degrees as the vertical incidence angle of the transmit antenna viewed from the building clutter, h_{Tx} and h_{Rx} are the transmit and receive antenna heights in meters, respectively, h_c is building clutter height in meters, d or d' is two-dimensional (2-D) or 3-D distance in meters between the transmit and receive antennas, and d_c is distance in meters between the clutter (building) and the receive antenna. Elevation angle, θ, is given by

$$\theta \text{ [degrees]} = \tan^{-1}\left[(h_{Tx} - h_c) \;/\; (d - d_c)\right]. \quad (2)$$

In practice, a transmitted signal is assumed to be diffracted or reflected from the roof or the rooftop of buildings as shown by the solid blue line in Fig. 1. On the other hand, it transmits a signal through the building as indicated by the solid red line. It collided with the building behind it at double intervals and was reflected several times. Finally, signals with additive excess loss due to building shadowing are received by receiver (R_x).

B. ITU-R Slant Path Model

The existing ITU-R model (Recommendation ITU-R P.2108) [11] in the slant path link describes the deterministic clutter loss model. The ITU-R model was created based on deterministic ray tracing mechanism. The ITU-R model, which does not exceed the locational probability, p, in percentile, has both frequency K_1 and elevation angle effect and is given by (3). K_2 and K_3 were reflected for calculating the specular reflection and controlling elevation angle.

$$L_{ces} \text{ [dB]} = \left\{-K_1 \left[\ln(1 - p/100)\right] \cot(K_2)\right\}^{K_3} - 1 - 0.6Q^{-1}(p/100) \quad (3)$$

where the fundamental frequency function $K_1 = 93({f_{\mathrm{GHz}}}^{0.175})$, and the elevation angle functions $K_2 = [0.5(1 - \theta/90) + \pi\theta/180]$ as well as $K_3 = [0.5(90 - \theta)/90]$.

C. Warfisch–Ikegami Model

Clutter loss can be derived from the deterministic path loss model but not the empirical model. The COST 231 Warfisch–Ikegami model (W-I model) [8] is a physical site-specific propagation model considering multipath between buildings from rooftop diffraction. There are no considerations of topographical database. It is assumed that all buildings are the same average building height. Excess loss by the W-I model is given by

$$L_{WI} \text{ [dB]} = L_{rts} + L_{msd}. \quad (4)$$

where L_{rts} is excess loss associated with diffraction up to the street level, and L_{msd} is excess loss propagated up the roof by multiple diffraction through the building.

D. Modified Warfisch–Bertoni Model

The modified Warfisch–Bertoni model (W-B model) [13] covering up to millimeter bands is the deterministic model similar to the W-I model, too. This model is also a physical propagation model considering multireflective paths between buildings from mainly rear building reflection. Excess loss based on the W-B model is given by

$$L_{WB} \text{ [dB]} = L_{msd} + \min(L_{mr}, L_{rts}) \quad (5)$$

where L_{msd} is loss propagated up the roof by multiple diffraction through the remodeled roof path, L_{mr} is multiple reflection loss between buildings, and L_{rts} is loss related to diffraction loss in the street level.

TABLE I
MEASUREMENT CAMPAIGN AND PARAMETERS

Measurement parameters	Korea data	Japanese data
environment	urban(Cheongju)	urban(Kanagawa)
frequency (f)	2.19, 4.99, 10.03 GHz	3.3, 5.7 GHz
Tx antenna height (h_{Tx})	73.6 m	150 m
Rx antenna height (h_{Rx})	1.8 m	3 m
elevation angle (θ)	$9^\circ - 39^\circ$	$3^\circ - 28^\circ$
average building height (h_c)	9 – 23 m	10 – 15 m
average building width (d_c)	17 m	15 m
Tx–Rx distance (d)	80 – 340 m	270 – 2800 m

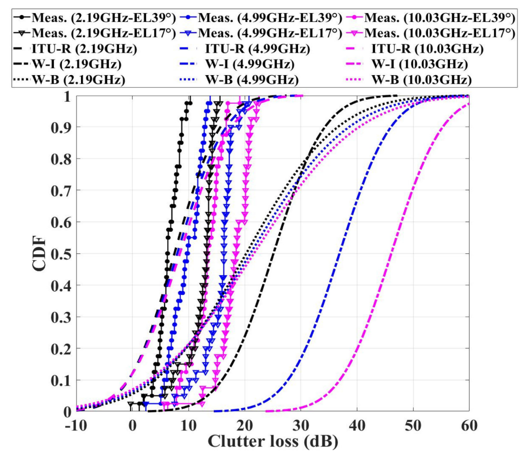

Fig. 2. Comparison of measured data and clutter losses in the existing models (ITU-R, W-I, and W-B) at frequencies of 2.19, 4.99, and 10.03 GHz.

III. VALIDATION OF EXISTING PREDICTION MODEL

A. Measurement Environment and Data Utilization

For the comparison between existing models (ITU-R, W-I, and W-B model) and the measured data, the measurement data provided by the ITU-R correspondence group (CG) databank [14] were used. Sampling data for slow or fast fading decorrelation were obtained by averaging 36 measured data from Korea and the 20 measured data from Japan at each measurement point in different urban environments. A total of 17 108 measured data from Korea and Japan were applied to reflect different regional environments below 10 GHz. The parameters of the detailed measurement data are in Table I.

The databank of clutter loss measurements is being created in ITU-R CG 3K-3M-12. Urban environments include various types of residential and commercial buildings and the planned roads.

B. Comparison Between Existing Models and Measurement

The empirical results of the statistical cumulative distribution function (CDF) were compared.

As shown in Fig. 2, the precision of clutter loss models was analyzed by comparing each existing model (ITU-R, W-I, and W-B model) and the statistical measured data at 2.19, 4.99, and

10.03 GHz below 10 GHz. In Fig. 2, the solid lines with circle markers depict the measured data in the elevation angle (EL) of 39° at 2.19, 4.99, and 10.03 GHz, and the solid lines with inverted-triangle markers depict the measured data in EL 17°. The other dashed lines represent clutter losses in the existing ITU-R model. The other dashed-dotted lines and dotted lines represent clutter losses in the existing W-I and W-B models, respectively. Let us note that clutter losses based on the measured data are related to frequency. There is a relatively CDF trend of lower loss for the higher elevation angles. The CDF trend for excess losses in the existing models is mostly underestimated or overestimated when compared with the measured data. In view of these results, it is necessary to improve the existing models by considering additional factor (parameter).

IV. Model Proposition And Modeling Process

As mentioned in Section I, the existing excess loss predictive models of geometric or deterministic methods have limitations, which do not reflect the realistic scattering and multipath effects due to nonuniform building height as well as complex rooftop structures in urban even considering the average building height. We know that these environmental structures act as unpredictable obstacles that interfere with the propagation of the slant path link. For analysis based on measurement, we used the reliable measurement data from Korea and Japan in Table I. We defined three major factors in the proposed model: frequency and elevation angle as the parameters reflected in the existing ITU-R model, and average clutter (building) height as new parameter that can additionally affect excess loss characteristics.

In the new empirical model proposal, the reasons for adding new factors and changing parameter values in response to the existing ITU-R model are described in detail as follows.

1) Clutter loss is basically affected by frequency and multiple reflections between clutters in microwave frequency bands.
2) The existing ITU-R model has the disadvantage that it can be applied only in the 10 GHz frequency bands or higher, not in the lower frequency below 10 GHz.
3) The existing ITU-R model simply defines the elevation angle as the incidence angle of the transmit antenna viewed from the building clutter. However, the effect of clutter heights due to frequencies in the area of building clutter where the receiving antenna is placed cannot be ignored unlike the existing ITU-R model. We guess additional parameters are needed to give more accurate values than the ITU-R model when considering the actual radio wave urban environment.

A. Modeling and the Effect of Key Factors

Figs. 3–5 show the results of regression analysis related to major factor effect. Each regression function is derived from the measured data in Table I. First, clutter loss increases as the frequency increases as shown in Fig. 3. The fundamental frequency function is expressed as K_1. Second, clutter loss increases as the elevation angle decreases in Fig. 4. The elevation angle function is expressed as K_2 and K_3 and is related to frequency. Third, clutter loss increases as the average clutter height increases. The slope of the curve of clutter loss decreases as the frequency increases in Fig. 5. In this letter, a new environment function as a key factor in the proposed empirical model based on the measured data is expressed as C_{var} with the relationship between frequency and the average clutter height. The optimized fitting parameter values according to each factor below 10 GHz are provided as more accurate values.

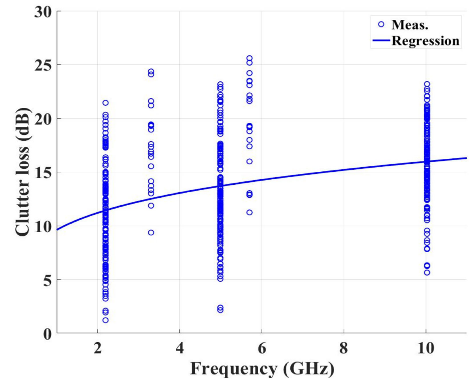

Fig. 3. Regression result and measured data according to the frequency.

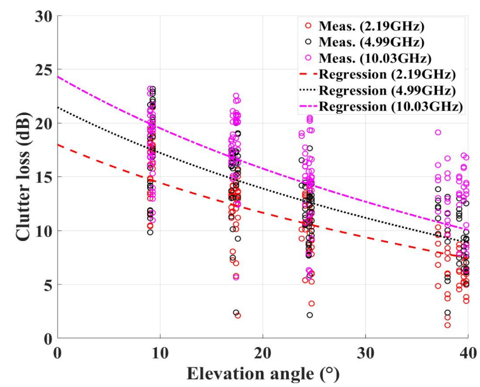

Fig. 4. Regression results at frequencies of 2.19, 4.99, and 10.03 GHz and measured data according to elevation angle.

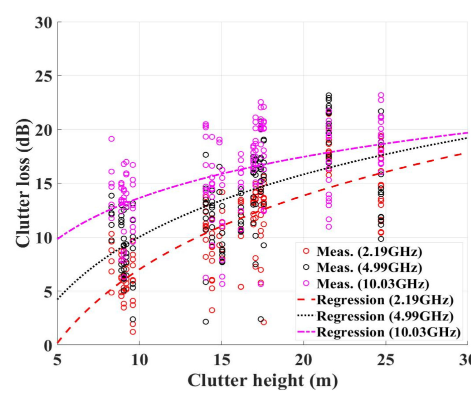

Fig. 5. Regression results at frequencies of 2.19, 4.99, and 10.03 GHz and measured data according to average building (clutter) height.

B. Proposed Empirical Excess Loss Model

The proposed model by (6) is expressed as functions with (7) and (8). Unlike the existing models by (3)–(5), the proposed model is based on the measurement data. The statistical CDF distributions below 10 GHz frequency bands were found to be well fitted by making K_1, the function of frequency. The

TABLE II
MEASUREMENT CAMPAIGN AND PARAMETERS FOR CROSS-VERIFICATION

Measurement parameters	Korea data	Japanese data
environment	urban(Cheongju)	urban(Tokyo)
frequency (f)	4.99 GHz	1.5 GHz
Tx antenna height (h_{Tx})	56.11 m	340 m
Rx antenna height (h_{Rx})	1.5 m	2.5 m
elevation angle (θ)	$9.5^{\circ}-22.7^{\circ}$	$13^{\circ}-54^{\circ}$
average building height (h_c)	7.4 – 15 m	6 – 42 m
average building width (d_c)	22.7 m	20 m
Tx–Rx distance (d)	117.5 – 302.8 m	235 – 1296 m

TABLE III
RMSE RESULTS IN SELF- AND CROSS-VERIFICATION

RMSE (dB)	Self-verification					Cross-verification	
	2.19 GHz	3.3 GHz	4.99 GHz	5.7 GHz	10.03 GHz	1.5 GHz	4.99 GHz
ITU-R	5.03	6.68	7.02	8.08	9.21	8.14	6.3
W-I	14.9	26.2	24.1	26.6	30.9	8.56	16.9
W-B	13.5	15.8	13.4	16.2	14.3	11.52	8.19
Proposed	3.04	4.74	3.61	4.31	3.71	3.06	3.57

cotangent expression at the elevation angle recognizes the dominance of specular reflection in clutter loss [12]. An additional parameter, C_{var}, is newly given as the measurement environment variable correlated with the operating frequency and average clutter height in (8).

$$L_{\text{prop}}\left(f_{\text{GHz}}, \theta, h_c\right)\ [\text{dB}] = L_{\text{pes}} + C_{\text{var}} \tag{6}$$

$$L_{pes}\ [\text{dB}] = \left\{-K_1\left[\ln\left(1-p/100\right)\right]\cot\left(K_2\right)\right\}^{K_3} - 0.1\sigma Q^{-1}\left(p/100\right) \tag{7}$$

$$C_{\text{var}} = -0.06 f_{\text{GHz}} h_c + 0.5 h_c + 5.0 {f_{\text{GHz}}}^{0.59} - 9.7 \tag{8}$$

where the fundamental frequency function, $K_1 = 93\left({f_{\text{GHz}}}^{0.22}\right)$, and the elevation angle functions $K_2 = \left[0.61\left(1-\theta/90\right) + \pi\theta/180\right]$ as well as $K_3 = \left[0.6(90-\theta)/90\right]$. h_c the average clutter height in meters, and Q^{-1} the inverse normal distribution function [11]. The variation of all measurement data have the standard deviation of σ dB. Let me note that the accuracy of the proposed model reflecting the realistic clutter structures rather than the geometric and deterministic model reflecting only the uniform characteristics of the clutter can be improved.

V. RESULTS AND EXPERIMENTAL VALIDATION

For the validation of the proposed model, self-verification and cross-verification in different urban environments were performed using the measured data in Tables I and II from Korea and Japan, respectively. As results, root-mean-square error (RMSE) values for existing models as well as the proposed model are summarized in Table III to provide the relative accuracy corresponding to the measurement data.

$$\text{RMSE}\ [\text{dB}] = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(P_{pi} - P_{mi}\right)^2} \tag{9}$$

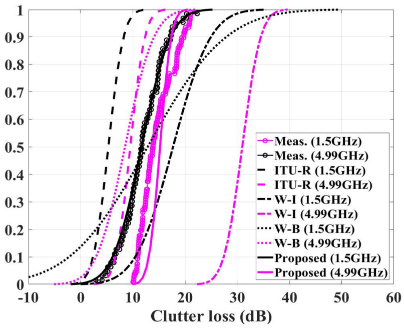

Fig. 6. Cross-verification of the proposed model based on the measured data and comparison results between models at 1.5 and 4.99 GHz frequencies.

where P_{pi} is the predicted clutter loss value in dB for one sample index i ($i = 1, 2, 3, \ldots, N$) in each model and P_{mi} is the measured clutter loss value in dB. N depicts the maximum number of measurement data samples.

As the first results, the RMSE values of the proposed model in self-verification is the lowest at about 3–5 dB. The next is result in cross-verification as shown in Fig. 6. We demonstrated the new measured data in Table II, different from the measurement data in Table I used to develop the model, in order to further prove the validity of the proposed empirical model. The comparison graphs of the existing model to verify the accuracy of the proposed empirical model are given as the CDF of clutter losses at frequencies of 1.5 and 4.99 GHz. The RMSE values of the proposed model in cross-verification are the lowest as about 3–4 dB rather than RMSE values of existing models.

VI. CONCLUSION

Measurement data utilization and empirical modeling based on several key parameters such as frequency, elevation angle, and average clutter height were provided herein. It was found that realistic environmental characteristics such as both the height of residential and commercial buildings and complex rooftop structures act as obstacles to the radio propagation of the slant path link between the earth station and the satellite station in urban affect additional excess loss. As results of the analysis, conventional prediction models did not fit well when compared with the data measured in various urban environments. Thus, we developed and proposed the new empirical clutter loss model. The proposed model was verified using the reliable measurement data from Korea and Japan. As results in the self-verification and cross-verification, the measured data as well as the proposed model were presented as RMSE values that can be compared with other existing models in accuracy. Compared to the existing predictive model based on geometric and deterministic modeling, the newly proposed empirical model based on measurement in real environment has improved RMSE performance and breaks through the limitations of approximate modeling in site-specific modeling. In conclusion, the new proposed empirical excess loss model can be used as an indicator for designing communication links.

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