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# Effect Level Based Parameterization Method for Diffuse Scattering Models at Millimeter-Wave Frequencies

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**ABSTRACT** This paper proposes a multi-coefficient estimation method for the dielectric parameters of rough materials and an effect level-based parameterization method for diffuse scattering models to characterize and model the diffuse scattering propagation at millimeter-wave frequencies. A series of diffuse scattering propagation measurements and simulations for rough materials have been performed at 40–50 GHz in a typical indoor scenario. Theoretical reflection coefficient, transmission coefficient, and scattering coefficient of rough materials, which are requisite for the proposed estimation method, are derived based on the Fresnel theoretical model and the Gaussian rough surface model. The directive model and double-lobe model are chosen and integrated with ray tracing tool to simulate the diffuse multipath propagation for rough materials based on effect level evaluation results. The optimal model parameters are obtained and various simulation results are compared and in particular, the estimated ranges of scattering coefficients agree well with the measured values. The investigations demonstrate that the proposed parameterization method is reliable and accurate for the diffuse scattering models and can be applied for the determination of model parameters from extensive materials measurement data, especially for millimeter-wave channel analysis and modeling.

**INDEX TERMS** Millimeter-wave, diffuse scattering, model parameterization, effect level, propagation coefficients, rough materials.

## I. INTRODUCTION

Millimeter-wave (mmWave) bands have attracted more attentions to satisfy the increasing demand for ultra-high-speed data transmission in wireless communications [1]–[3]. In radio propagation at the low and medium frequency bands below 6 GHz, multipath components resulted from diffuse scattering (DS) have been commonly neglected as the surface irregularities are much less than the wavelength. However, many recent studies have demonstrated DS makes a more significant impact on the time and angle dispersion of mmWave radio signals since the irregularities of some rough materials are comparable to the short working wavelength [3]–[5]. Therefore, contributions of DS are considerable for evaluating the multipath propagation characteristics to achieve accurate mmWave channel modeling.

The ray tracing (RT) method based on the geometrical optics (GO) theory has been widely adopted in the simulation for radio propagation, and its integration with DS models enables greater performance at mmWave bands for the better quasi-optical characteristic [6]–[8]. However, feasibility studies on DS models and model parameters for various materials at wideband mmWave are not enough for accurate multipath propagation prediction. The early Beckmann-Kirchhoff

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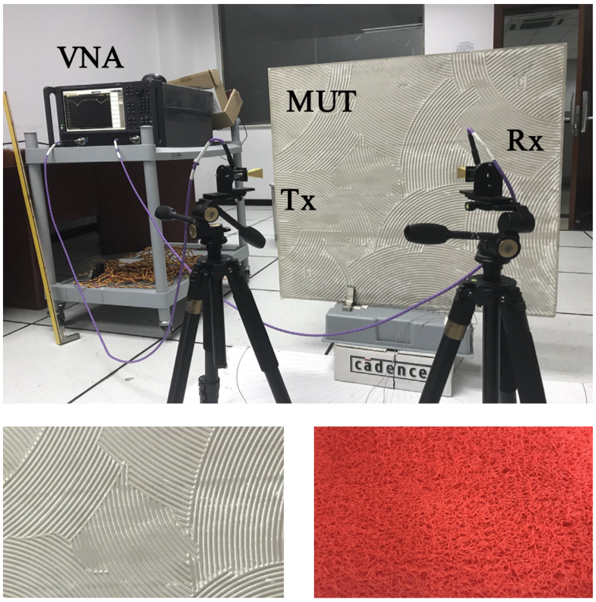
scattering theory described in [9] gave the solution to analyze DS characteristics under paraxial assumption based on Kirchhoff boundary condition. In [10], the two-dimension DS mechanism was analyzed and the ''effective roughness'' (ER) model was proposed through ray approach. And based on the ER model, three DS models representing different scattering patterns were proposed in [11]. The Lambertian model and directive model were embedded into the RT algorithm to obtain the optimal model parameters for several typical building walls by tuning parameters for the best fit with measurements at 1296 MHz. However, selection for the initial values of scattering coefficient and dielectric parameters in [11] was empirical and errors might exist due to uncertainty for the practical characteristics of materials under test (MUT). In [12], different DS models respectively embedded into RT simulation tool have been compared in an office room at Terahertz frequencies, but only propagation on walls and ground was involved. In [13], the impacts of diffuse multipath components and scattering model parameters on the indoor radio propagation have been studied at 60 GHz. Through the RT tool incorporated with the Lambertian model and directive model, model parameterization for several wall materials was performed and propagation characteristics at 60 GHz in an indoor scenario were also analyzed based on the best-fit model parameters. However, model parameterization in [13] was based on tuning all possible values of model parameters including the scattering coefficients of MUT, which was relatively complex.

In previous studies, the dielectric parameters of MUT used in RT simulation are commonly obtained from some previous references and standards, which can be different from practical materials and therefore decrease simulation accuracy. In addition, although directive model has been validated at some specific frequencies, it still needs to be investigated in complex environments including various materials at mmWave bands. Furthermore, few studies have focused on double-lobe model suitable for surfaces with very protruding irregularities, and diffuse scattering propagation measurements at wideband mmWave are also not enough to study the frequency correlation of model parameters.

Two contributions of this paper are as follows.

1) The multi-coefficient estimation method for dielectric parameters has been proposed to improve the estimation accuracy compared to the conventional tuning method based on reflection coefficient, and consequently RT simulation errors resulted from the parameter initialization can be decreased relative to adopting the standard dielectric parameters of materials.

2) The parameterization method for DS models based on the effect level evaluation has been proposed to improve the reliability of tuning procedure for model parameters compared to the conventional variable-controlling method. In addition, this proposed method does not need to adjust the scattering coefficient in the whole range [0, 1] and can be validated more easily by comparing with measured values. Therefore, the diffuse multipath propagation characteristics can be analyzed based on the estimated model parameters for rough materials at mmWave frequencies.



Rough rock Plastic carpet

**FIGURE 1.** **Measurement setup and photographs of MUT.**

**TABLE 1.** **Dimensions and roughness parameter values of MUT.**

| Material | Length (cm) | Width (cm) | Thickness (cm) | Std. dev. (μm) |
|---|---|---|---|---|
| Rough rock | 79.55 | 80.95 | 1.188 | 70.48 |
| Plastic carpet | 147.32 | 117.65 | 1.084 | 990.89 |

The rest of paper is organized as follows. Indoor diffuse scattering propagation measurement based on the free space method is presented, and the optimal dielectric parameters of MUT are obtained using the proposed multi-coefficient method in Section II. Effect levels on the received power distribution are evaluated for different model parameters, and parameterization method based on the evaluation results is proposed for DS models in Section III. The RT simulations integrated with DS models are performed and results of model parameterization are analyzed in Section IV. Conclusions are drawn in Section V.

## II. MEASUREMENT SETUP AND PROPAGATION COEFFICIENTS

In-site diffuse scattering propagation measurements have been performed in a typical indoor scenario. The measurement setup and photographs for the two types of parameterized MUT are given in Fig. 1. The dimensions and roughness of MUT have been measured in a quantitative way and recorded in Table 1. We can appreciate that the rough rock commonly used as building material is relative rough whereas the plastic carpet considered as indoor decorative material presents more protruding irregularity.

**TABLE 2.** System parameters of measurement platform.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Center frequency | 45 GHz | IF bandwidth | 2 kHz |
| Bandwidth | 10 GHz | TX power | -4 dBm |
| Sweep count | 1001 | Measured radius | 0.5 m |
| Frequency step | 10 MHz | TX incident angle | 30° |
| Polarization type | vertical | RX step angle | 15°/5° |

**TABLE 3.** The minimum RMSE comparison between the conventional and proposed methods.

| MUT | Conventional tuning method | Multi-coefficient method | Enhanced accuracy | Optimal dielectric parameters $\varepsilon$ | |
|---|---|---|---|---|---|
| | | | | $\varepsilon'$ | $\sigma$ |
| Rough rock | 0.0602 | 0.0475 | 21% | 4.60 | 0.31 |
| Plastic carpet | 0.0336 | 0.0198 | 41% | 2.17 | 0.08 |

For the measurement setup, a pair of vertically polarized wideband horn antennas (working at 40-60 GHz) was mounted on tripods with the height of 67 cm from the ground as the transmitter (TX) and receiver (RX) respectively, and connected to a N5235B vector network analyzer (VNA) operated from 100 MHz to 50 GHz. The pair of connecting RF cables has a length of 3 m and the total loss is 20 dB at 45 GHz. And the TX antenna always illuminated the center of MUT from a static direction at 60°, i.e., the incident angle is 30° out of the normal direction.

In reflection coefficient measurement, the TX and RX antennas were positioned on the same side of MUT and at a distance of 50 cm from the impact point on MUT surface to satisfy the far field condition. Both antennas pointed toward the center of the MUT, and the RX antenna was placed in the specular direction of TX antenna. While, in diffuse reflection measurement, the RX antenna was moved along a half circumference on $N$ evenly spaced positions. The value of $N$ depends on the RX step angle, which was set as 15° and 5° for the rough rock and plastic carpet respectively. As for the transmission coefficient measurement, the RX antenna was fixed at the symmetrical position of the TX about the center of MUT. In addition, the time gating technique was used to reduce the impact of unwanted multipath components and noise. System parameters of the measurement platform are summarized in Table 2. And the derivation for scattering coefficients and dielectric parameters of MUT is introduced as follows, which are requisite for initializing RT simulation.

Since the amplitude and phase information of frequency domain recorded in $S_{21}$ parameters, which represent the power loss of incident signal in present work, can be divided into two parts, one is the desired diffuse reflection or transmission components from MUT, the other is composed of path loss, cable loss and antenna radiation pattern. In order to eliminate the effects of unwanted components from the latter part for the calculation of the measured reflection coefficient $\Gamma_{\mathrm{mea}}$ and transmission coefficient $T_{\mathrm{mea}}$, reference measurements were performed by replacing MUT with metal slab and air respectively. Therefore, $\Gamma_{\mathrm{mea}}$ and $T_{\mathrm{mea}}$ are expressed as:

$$\Gamma_{\mathrm{mea}} = \frac{S_{21,\mathrm{MUT}}}{S_{21,\mathrm{metal}}} \tag{1}$$

$$T_{\mathrm{mea}} = \frac{S_{21,\mathrm{MUT}}}{S_{21,\mathrm{air}}}, \tag{2}$$

where $S_{21,\mathrm{MUT}}$ and $S_{21,\mathrm{metal}}$ represent the measured $S_{21}$ with the MUT and metal slab respectively, and $S_{21,\mathrm{air}}$ is the reference value without material slab. Then based on the definition of propagation coefficients and power balance, measured scattering coefficient $S_{\mathrm{mea}}$ can be expressed as:

$$S_{\mathrm{mea}} = \sqrt{1 - \Gamma_{\mathrm{mea}}^2 - T_{\mathrm{mea}}^2} \tag{3}$$

According to the well-known Fresnel theoretical model, the reflection and transmission coefficients are determined by dielectric parameters [14]. And the conventional method to estimate dielectric parameters as shown in [15] is tuning the theoretical reflection coefficients to match with the measured values based on the Fresnel theoretical model. However, as the impact of DS gets greater at mmWave bands, this method can yield more estimation errors.

A multi-coefficient estimation method is proposed in present work to obtain more accurate complex dielectric parameter $\varepsilon$ of MUT, which is to achieve the minimum root mean square error (RMSE) between the theoretical coefficients and measured values by adjusting the reflection coefficient, transmission coefficient and scattering coefficient jointly. The realization process of the proposed method is as follows.

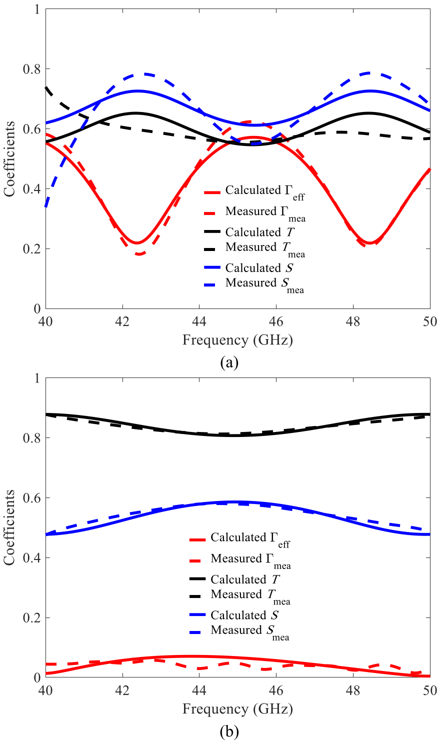
*Step1:* The effective reflection coefficient $\Gamma_{\mathrm{eff}}$ and transmission coefficient $T$ are derived by combining the Fresnel theoretical model for the single-layer slab with the Gaussian rough surface model.

*Step2:* The scattering coefficient $S$ can be calculated by making use of the equation (3).

*Step3:* The minimum RMSE can be achieved by varying the dielectric parameters to adjust three coefficients jointly.

Numerical comparison for the minimum RMSE between the two estimation methods and the optimal dielectric parameters of MUT are given in Table 3, where $\varepsilon'$ and $\sigma$ are the permittivity and conductivity respectively. The minimum RMSE of the proposed method are 0.0475 and 0.0198 for the rough rock and plastic carpet respectively, which achieve 21% and 41% accuracy improvement compared to the conventional reflection coefficient tuning method. And a more remarkable improvement can be observed for the plastic carpet, this is because the impact of diffuse scattering is greater due to its more protruding surface irregularity.

Moreover, good agreements between the calculations and measurements for the reflection coefficient, transmission coefficient and scattering coefficient are shown in Fig. 2 using the optimal dielectric parameters. And the results also indicate propagation characteristics especially at wideband



(a)

(b)

**FIGURE 2.** **Calculated (solid line) and measured (dotted line) propagation coefficients for the (a) rough rock and (b) plastic carpet.**

mmWave have the remarkable property for considered rough materials, that is the propagation coefficients show an obvious Fabry-Pérot resonance phenomenon, rather than the simple monotonicity in frequency domain.

## III. PARAMETERIZATION METHOD BASED ON EFFECT LEVEL EVALUATION FOR DIFFUSE SCATTERING MODELS

Through primary measurement data analysis, distinct diffuse scattering propagation phenomena out of the specular reflection direction were observed, and different distributions of received power were also found for the two MUT. The received power distribution is steered toward the specular reflection direction for the rough rock, which agrees with the scattering pattern of directive model. And for the plastic carpet, received power distribution is fairly dispersive and the backscattering phenomenon is considerable, which is similar with double-lobe model. Therefore, directive model and double-lobe model have been chosen to parameterize the rough rock and plastic carpet respectively, and effect level evaluation for model parameters is as follows.

### A. DIRECTIVE MODEL

The expression for the diffuse electric field of directive model is:

$$\begin{aligned}\left|\overline{E_S}\right|^2 &= E_{S0}^2 \cdot \left(\frac{1+\cos\psi_R}{2}\right)^{\alpha_R} \\ &= \left(\frac{SK}{r_i r_S}\right)^2 \frac{dS\cos\theta_i}{F_{\alpha_R}} \cdot \left(\frac{1+\cos\psi_R}{2}\right)^{\alpha_R} \qquad (4)\end{aligned}$$

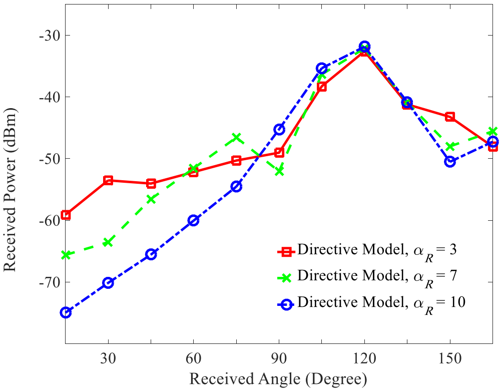


**FIGURE 3.** **Evaluation results for $\alpha_R$ of directive model at 45 GHz.**

Therefore the scattering pattern of directive model can be characterized by $\Theta_D \triangleq \{S, \alpha_R, \theta_i, \psi_R, r_i, r_s\}$, where $\theta_i$ is the incident angle, $\psi_R$ is the angle between specular reflection direction and scattering direction, $r_i$ is the distance between the TX and the impact point on MUT, $r_s$ is the distance between the RX and the impact point. And the key for directive model parameterization is to tune the scattering coefficient $S$ and the width factor $\alpha_R$ of scattering lobe.

According to the definition, $S^2$ determines the proportion of scattered power from total incident power. Effect level evaluation for $\alpha_R$ on received power with the given $S$ is reported in Fig. 3. It can be observed that $\alpha_R$ mainly affects the scattered power and angle spread width, that is the greater $\alpha_R$, the smaller power and the narrower width.

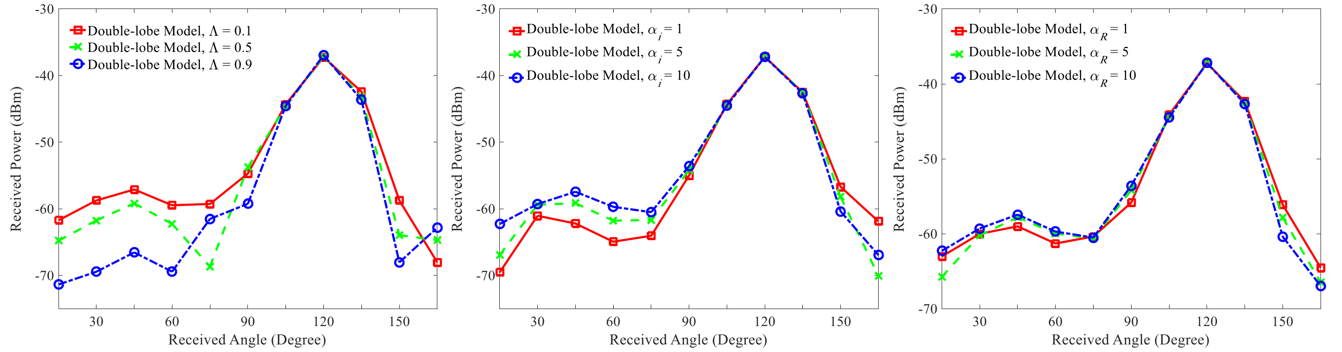
### B. DOUBLE-LOBE MODEL

When the surface presents very protruding irregularity like the plastic carpet in present work, the backscattering components around the incident direction should be included into DS model. Similar to directive model, which is also named as single-lobe model, the diffuse electric field of double-lobe model can be written as [11]:

$$\begin{aligned}\left|\overline{E_S}\right|^2 = \left(\frac{SK}{r_i r_S}\right)^2 \frac{dS\cos\theta_i}{F_{\alpha_i,\alpha_R}} \cdot [\Lambda(\frac{1+\cos\psi_R}{2})^{\alpha_R} \\ +(1-\Lambda)(\frac{1+\cos\psi_i}{2})^{\alpha_i}] \qquad (5)\end{aligned}$$

The parameters set characterizing the scattering pattern of double-lobe model can be expressed as $\Theta_{D-L} \triangleq \{S, \alpha_R, \alpha_i, \Lambda, \theta_i, \psi_R, \psi_i, r_i, r_s\}$, where $\alpha_i$ is the width factor of the scattering lobe along incident direction, $\Lambda$ is the partition factor of scattered power in the two scattering lobes, $\psi_i$ represents the angle between the incident direction and scattering direction. And parameterization for double-lobe model is to estimate the optimal $S$, $\alpha_R$, $\alpha_i$ and $\Lambda$.

Fig. 4 illustrates how double-lobe model parameters affect the received power distribution with the given $S$. It can be concluded $\Lambda$ shows the maximum effect level on received power distribution, and the proportion of backscattering components is reduced when $\Lambda$ is increased. The moderate effect level is resulted from $\alpha_i$, and greater $\alpha_i$ increases backscattering



(a) (b) (c)

**FIGURE 4.** Evaluation results for double-lobe model parameters: (a) Λ, (b) $\alpha_i$ and (c)$\alpha_R$ at 45 GHz.

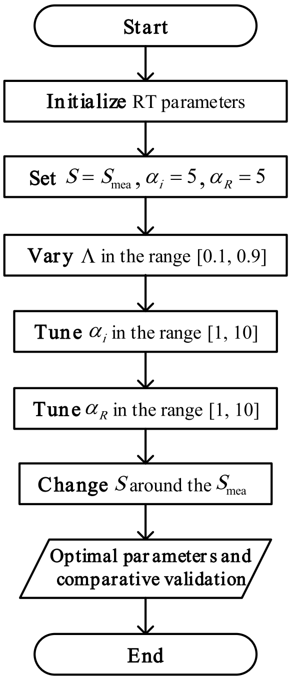


**FIGURE 5.** Parameterization procedure for double-lobe model.

power because angle spread out of the incident direction is narrower while $S$ remains constant. And $\alpha_R$ shows the minimum effect level which only does little effect on the angle spread width of received power around the specular direction.

## C. EFFECT LEVEL BASED PARAMETERIZATION METHOD

The evaluation of effect levels on received power distribution for DS model parameters is of critical importance for improving the reliability of tuning procedure in previous works. The reason is that parameterization for DS models as can be seen in [11] and [13], the initial parameters values are empirical and the tuning order is arbitrary, which have technical drawbacks in two aspects. One is the uncertainty for initial parameters values and lack for overall comparisons increase the possibility to reach the local optimal values. The other is that the tuning order for model parameters has not been emphasized, which may work for the Lambertian model and directive model with only two parameters to estimate, but the feasibility for double-lobe model with four key parameters needs to be further investigated. Moreover, parameterization results in previous works also lack for appropriate validation. Therefore, a more reasonable and systematic parameterization method is necessary especially for double-lobe model. And in present work, the parameterization method combining the variable-controlling principle with effect level evaluation results is proposed and validated for directive model and double-lobe model respectively.

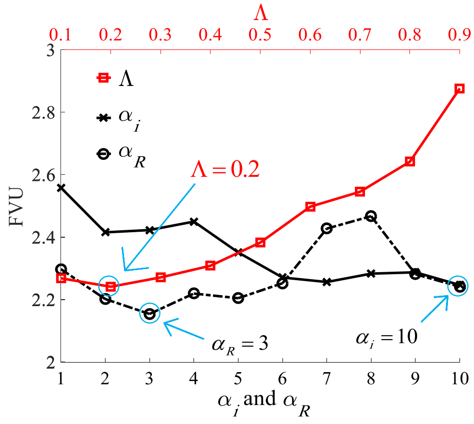


**FIGURE 6.** FVU errors of Λ (red solid line), $\alpha_i$ (black solid line) and $\alpha_R$ (black dotted line) for the plastic carpet at 45 GHz when S = 0.58.

Based on evaluation results, the two-step parameterization method for directive model is as follows.

*Step 1 (Estimation of Scattering-Lobe Width $\boldsymbol{\alpha_R}$):*

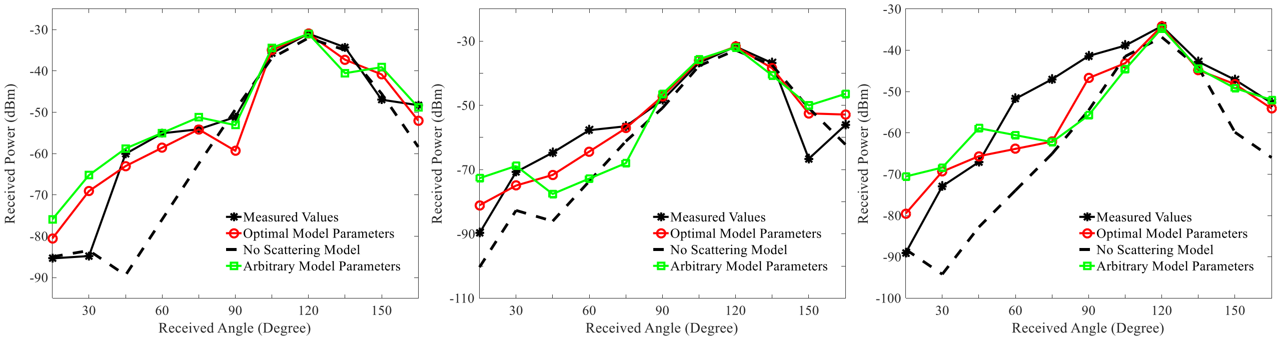
Set $S_{\mathrm{mea}}$ as the initial value of $S$ and vary $\alpha_R$ in the range [1, 10], then the measured received power $P_{\mathrm{mea}}$ is compared with the simulated $P_{\mathrm{sim}}$ to estimate the best-fit $\alpha_R$ by adopting the Fraction of Variance Unexplained (FVU) error evaluation function. The expression of FVU is:

$$FVU = \sqrt{\frac{\sum_{i=1}^{N} \left|P_{mea.i} - P_{sim.i}\right|^2}{\sum_{i=1}^{N} \left|P_{mea.i} - \overline{P_{mea.i}}\right|^2}}, \tag{6}$$

where $N$ is the index of receiver positions.

**TABLE 4.** Summary of model parameterization results and validation.

| Material | Scattering model | Frequency (GHz) | Best-fit model parameters $\alpha_R$ | $\alpha_i$ | $\Lambda$ | Minimum FVU | Best-fit range of $S$ | Measured value of $S_{\text{mea}}$ |
|---|---|---|---|---|---|---|---|---|
| Rough rock | Directive model | 40 | 10 | -- | -- | 0.3560 | 0.2-0.4 | 0.35 |
| | | 45 | 10 | -- | -- | 0.3693 | 0.4-0.6 | 0.55 |
| | | 50 | 10 | -- | -- | 0.4398 | 0.5-0.7 | 0.68 |
| Plastic carpet | Double-lobe model | 40 | 5 | 7 | 0.3 | 1.2729 | 0.5-0.6 | 0.48 |
| | | 45 | 3 | 10 | 0.2 | 1.4289 | 0.6-0.7 | 0.58 |
| | | 50 | 3 | 10 | 0.2 | 1.0735 | 0.5-0.6 | 0.50 |



(a) (b) (c)

**FIGURE 7.** Comparisons between measured values and simulation results at (a) 40 GHz, (b) 45 GHz, (c) 50 GHz for the rough rock.

*Step 2 (Scattering Coefficient Estimation via FVU):* Use the best-fit $\alpha_R$ obtained in step (1) and change $S$ around the $S_{\text{mea}}$. Since the FVU errors reach the minimum with the optimal parameters, the appropriate range of $S$ for the MUT can be estimated according to FVU errors comparison, and fluctuation within 0.1 around the optimal value is acceptable in present work. Furthermore, the proposed parameterization method can be validated when $S_{\text{mea}}$ is in the range, which has not been mentioned in previous works.

As for double-lobe model, the estimation for multiple parameters increases the difficulty to reach the best fit between measurements and simulations, but it still can be achieved through the evaluation for effect levels of different model parameters. At the same time, compared to the common parameterization method of controlling variables for multiple parameters, tuning model parameters from the maximum effect level to the minimum based on evaluation results can reduce estimation errors and improve the accuracy of double-lobe model parameterization. Therefore, the four-step parameterization method for double-lobe model is proposed as follows and corresponding flow chart is shown in Fig 5.

*Step 1 (Estimation of Power Partition Factor $\boldsymbol{\Lambda}$):* Set $S_{\text{mea}}$ as the initial value of $S$ while $\alpha_R$ and $\alpha_i$ are set as a moderate value, i.e., 5. Then vary $\Lambda$ in the range [0.1, 0.9] to estimate the best-fit $\Lambda$.

*Step 2 (Tuning Backscattering-Lobe Width Factor $\boldsymbol{\alpha_i}$):* Perform simulation using the best-fit $\Lambda$ and tuning $\alpha_i$ in the range [1, 10].

*Step 3 (Tuning Scattering-Lobe Width Factor $\boldsymbol{\alpha_R}$):* Tune $\alpha_R$ in the range [1, 10] using the best-fit $\Lambda$ and $\alpha_i$.

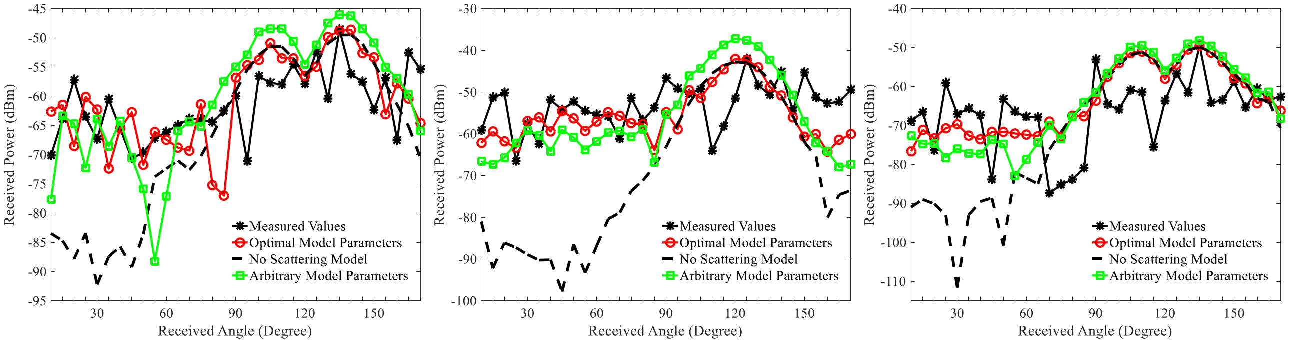
*Step 4 (Determination for Scattering Coefficient Range):* Change $S$ around the $S_{\text{mea}}$ to obtain the appropriate range of $S$ for validation.

It can be seen from the above proposed estimation procedure that the parameterization method based on effect level evaluation allows splitting the optimization problem required to jointly estimate multiple parameters into several single-parameter estimation problems.

## IV. ANALYSIS FOR SIMULATION RESULTS

Considering the contribution of DS to received power distribution for rough materials, a series of RT simulations integrated with DS models have been performed and analyzed based on proposed methods. An example of confirming the optimal model parameters according to FVU errors is shown in Fig. 6 for a fixed $S$ at 45GHz when double-lobe model is chosen for the plastic carpet. As can be seen in Fig. 6, the best-fit values of $\Lambda$, $\alpha_i$ and $\alpha_R$ are 0.2, 10 and 3 respectively when FVU errors reach the minimum value.

Further parameterization results are given in Table 4. It can be noticed the best-fit model parameters are closed at different frequencies for the same material, while scattering coefficients increase as frequency gets greater and show Fabry-Pérot resonance phenomenon as observed in Fig. 2. The $\alpha_R$ for the plastic carpet is smaller than the rough rock, which can be concluded that greater surface irregularity reduces the concentration of scattered power around the



(a) (b) (c)

**FIGURE 8.** **Comparisons between measured values and simulation results at (a) 40 GHz, (b) 45 GHz, (c) 50 GHz for the plastic carpet.**

specular direction. More importantly, good agreements between $S_{\text{mea}}$ and the best-fit ranges of $S$ are shown, which validate the proposed parameterization method.

Fig. 7 and Fig. 8 are comparisons between measured values and simulation results for received power distribution at different frequencies for the rough rock and plastic carpet respectively. It can be observed the maximum received power of the plastic carpet is lower than that of the rough rock, this is because not only the received power distribution is more dispersive, but also the reflection loss is greater for the plastic carpet with more protruding irregularity. Moreover, simulation results respectively with arbitrary model parameters and without DS components are also presented as reference. Power differences varying from 10dB to 30dB in DS directions can be found when DS is not considered and better fit with measured values can be obtained using the optimal model parameters, which prove the improvement of RT simulation accuracy using the proposed DS model parameterization method for rough materials at mmWave frequencies.

## V. CONCLUSION

This paper proposes a multi-coefficient estimation method for dielectric parameters and effect level based parameterization method for DS models at mmWave frequencies for rough materials. A series of diffuse scattering propagation measurements are carried out in a typical indoor scenario for initializing RT simulation and tuning model parameters. The estimation accuracy for dielectric parameters using the multi-coefficient method achieves 21% and 41% improvement respectively for the rough rock and plastic carpet. Moreover, it is concluded from effect level evaluation results that greater $\alpha_R$ of directive model results in smaller scattered power and narrower angle spread, $\Lambda$ and $\alpha_R$ of double-lobe model present the maximum and minimum effect levels respectively on received power distribution. Then RT simulations integrated with DS models are performed to parameterize MUT using proposed methods. The best-fit model parameters and various simulation results are compared at different frequencies, and the estimated ranges of $S$ agree well with measured values, which validates the proposed parameterization method in this paper.

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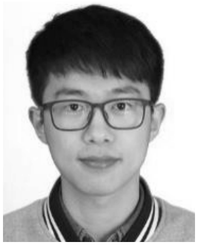

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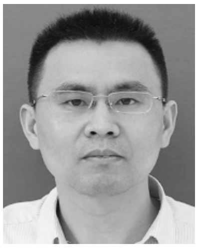

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