Electromagnetic Waves Scattering Distribution of Rough Surfaces at 60 GHz: Numerical and Analytical Modeling

Amir Sadaghiyani, Javad Ahmadi Shokouh, Hengameh Keshavarz

Faculty of Electrical and Computer Engineering, University of Sistan and Bluchestan, Zahedan, Iran.

ARTICLE INFO
Article history:
Received 25 July 2014
Received in revised form 8 July 2014
Accepted 15 September 2014
Available online 10 October 2014

Keywords:
Index Terms, Scattering Pattern, Ray-Tracing, Statistical Distributions, Channel Impulse Response, Home Flooring, 60 GHz;

ABSTRACT
The aim of this paper is study scattering distribution of electromagnetic waves in incident with rough surfaces, to improve the numerical modeling for propagation channel based on ray tracing (RT) at 60 GHz. So far the current numerical methods for modeling a vast propagation channel cover only simple mechanisms of propagation and they have not taken the scattering distribution to account. Therefore, there should be an integrated environment to show all factors. To reach this environment, Ray-Tracing-Engine (RTE), a tools for modeling the propagation environment in MATLAB, is presented. To focus on the main target of this dissertation, propagation channel is selected in 60 GHz frequency band. Because of specific characteristics of propagation in this frequency, the research of rough surfaces would be simplified. Following the configuration of propagation environment in RTE, roughness of surface will be determined by three distinguished methods. First, by the means of diverse statistical distribution, second, by the geometry of random rough surface from statistical process and third, by placing single-reflection statistical models from different angles and the effect of each of them in Channel Impulse Response (CIR) is studied. Finally, to verify the simulation results, for finding scattering pattern in 60 GHz from some kinds of home floor coverings, measurements has done based on sweeping frequency method by means of a Network-Analyzer in both Transverse Electric (TE) and Transverse Magnetic modes. In this research, three groups of conventional flooring are selected: finished floorings, subfloorings, and underlayments. Theoretical and experimental results lead to introduce statistical and mathematical models for wave scattering pattern on rough surfaces.

INTRODUCTION

To introduce electromagnetic wave propagation channel, numerical methods from accuracy point of view and also applying of propagation mechanism like reflection, transmission, refraction, diffraction and etc., are comparable experimental measurements.

They are also as simple and low profile as statistical mathematical models. Therefore using numerical tools based on ray tracing is a effective technique for vast and complicated propagation channels modeling which includes all geometrical specification and existed barriers in propagation environment (Kurner, T., 1993; Lawton, M.C. and J.P. McGeehan, 1994; Liang, G. and H.L. Bertoni, 1998; Hsueh-Jyh Li, 2000). However common waves propagation softwares such as radio waves propagation simulator (RPS) (Radiowave Propagation Simulator (RPS), Radioplan, 2013) from propagation factors uses only reflection, transmission, Refraction and diffraction (Lostanlen, Corre, 2003; Uguen, Lostanlen et al., 2002) which is not included be effect of scattering from rough surfaces. Because, including this scattering in a numerical way makes the software so complicated that the run of simulator becomes very time consuming. While for having an accurate propagation channel model to obtain the results very similar impulse responses measured all propagation factors should be included in the numerical method.

Almost every real surface that there are in different environment on rough and the effect of this roughness on waves scattering, has been the subject of research for decades. In general electromagnetic waves scattering can be categorized in two modes according to the roughness of the surface (Beckmann, P. and A. 1963). First the mode that the roughness of the surface is very small in comparison with the emitted wave length. In this type scattering phenomena is equivalent to specular reflection from a smooth surface, which in there reflected wave

Corresponding Author: Amir Sadaghiyani, Faculty of Electrical and Computer Engineering, University of Sistan and Bluchestan, Zahedan, Iran.
E-mail: amir.sadaghiyani@gmail.com
distribute its own energy in just one direction. In this mode according to the reflection rule, the angles are equal. Second mode occurs when there is increase in the roughness of the surfaces and it equal to the emitted wave length. In this type in addition to specular reflection, scattering factor appears where the reflected wave loses its energy by distributing in both specular and other directions.

Electromagnetic wave scattering from rough surfaces is applicable in other scopes of sciences such as remote sensing, medical imaging, radar imaging, geology and radio telecommunications (Bass, F.G. and I.M. Fuks, 1979), also lots of researches has been done, the issue of electromagnetic scattering from rough surface is still challenging. Because, wave scattering modeling from rough surface has its own complications. moreover, because of there is no precise report of existed roughness in different surfaces, electromagnetic scattering modeling cannot be count as a deterrent issue (Degli-Esposti, V., 2004). For this reason, presenting an integrated software with the consideration of the effect of roughness for studying the propagation of radio waves is always essential. Therefore the target is provision an improved software with inclusion of the roughness effect for studying electromagnetic wave scattering distribution and finding the mathematical model of it. To reach this target for modeling the propagation environment a tool so called RTE is presented. In this tool computations relevant to the propagation environment with its all factors are done in a integrated programming space in MATLAB (Ahmdi, J., 2009) software. RTE is suggested based on two dimensional (2D) RT calculations. According to this engine the position of transmitted and receiver can be selected in any point of simulated sample indoor environment. Then the effect of putting different rough surfaces in output is considered that is the same as the impulse response of the channel. In fact we are searching for a proper statistical mathematical model to make a pattern for wave scattering in incident to rough surface. To do this in simulated sample environment in RTE for introducing roughness three different methods has been used. This are:

1. Applying of different statistical distributions (Gaussian, uniform, exponential) for expressing roughness.
2. Geometrical modeling of random rough surfaces by processing of random Gaussian with exponential correlation function.
3. Placing single-reflection statistical models due to different angles as a representative of roughness. According to existence of compatibility and completion of this tool it can be used in preferred frequencies. For showing the consideration of this effect, we do it in 60 GHz frequency band. In fact this frequency band has specific propagation characteristic like high absorption loss (Rappaport, T S., 2002) that for this reason some propagation mechanisms such as transmission, Refraction, penetration and diffraction play fewer roles in computations (Song, H.B., 2009). Because of that modeling and describing electromagnetic wave distribution will simplified. Therefore to decrease calculating complications, these mechanisms are excluded. Hence, in the developed RTE, we only consider free space propagation, reflection and scattering. On the other hand, waves propagation in this frequency band is limited only to in room communication. Finally, it is just essential to introduce a room as a sample propagation environment. Because, in this band the frequencies do not pass waves through walls there is no need to simulate whole the building. In addition to this for evaluation the result of RTE, measurements are done for finding the scattering pattern of different home flooring in 60 GHz frequency and their statistical models and parameters are approximated. In this research, three groups of conventional home flooring are selected: finished-flooring materials, which are installed on top, sub floorings, which basically support the finished floorings in order to have a strong floor; and underlayments or carpet underlays, which are employed to make the carpet flooring even more comfortable.

To verify RTE the output is compared with the acquired output of the RPS commercial software. As mentioned above this software has the ability of studying wave propagations when all the smooth surfaces are even. The results show a good corresponds. Theoretical and experimental conclusions give Gaussian statistical-mathematical models for wave scattering pattern on rough surface.

The rest of the paper is organized as follows. In Section II, the design RTE with all details will be explained for a sample propagation environment. In Section III, The effect of different statistical models which are the indicator of roughness will be studied in CIR. Instead of considering different statistical model, rough surface itself will be made by statistical procedures for finding the function of electromagnetic waves scattering distribution in section IV. In fact in this section we will show which of statistical distributions that are used in the previous section can be substitute properly for a real rough surface. The effect of single reflection statistical models due to different angles in CIR will be considered in Section V which are another type of roughness. In section VI the applied structure of experimental measurements for finding scattering pattern of different floorings are explained. And then the result of numerical simulating and measurements for finding a proper mathematical model can be found in section VII. Finally, in section VIII the conclusion and suggestions for future work is presented.

Ray Tracing Engine:

Studies show that RT schemes are powerful numerical simulating tool for presenting propagation channel. This methods present reliable results comparing to experimental measurements to simulating propagation environment (Lee, H.S., 2009; Tayebi, A., 2009) and they are based on waves propagation modeling in space (Xia, H.H., 1996; Balanis, C.A., 1989). These methods also are used for forecasting the behavior of wave’s in
indoor and outdoor environments widely. In RT techniques, electromagnetic waves are basically assumed as rays. These computational electromagnetic methods categorizes as high frequency schemes which are developed based on Geometrical Optic (GO) (Degli-Esposti, V., 2009) and Geometrical Theory of Diffraction (GTD). The main goal in these techniques is the estimation of power, phase and delay received ray in the location of receiver. For this, properties of every received ray in receiver are needed. These results for obtaining side calculations are needed like calculation of received power in receiver spot. However the precise result due to of this method obtained by 3D modeling. 2D modeling not only reduces the volume of calculation significantly, but also gives the reliable results in comparison with 3D modeling (Zakharov, P., 2009). Because in this research the goal studying of the effect of scattering from rough surface in emission and reflection pane, therefore 2D model can be suitable for this research. There is plenty of commercial RT software, like RPS which has a good function in numerical simulating of propagation channel. While the effect of scattering from rough surface as one of propagation factors is not considered. It is obvious to have an accurate propagation channel model for acquiring very similar result to CIR measured all factors should be considered. So to solve the scattering issue of rough surface a integrated bed with all propagation factors based on numerical methods for RT should be designed. In this section, we propose a developed software based on RT methods performed on a sample environment. This sample environment is a room with the determined directions (2*4*3). Fig. 1 shows the 3D map of this indoor propagation environment. As explained before the frequency is adjusted in 60 GHz, so in propagation environment modeling only barriers and scatters are considered which their sizes are more than 10 milimeter. It means their size is twice greater than wave length in free space (Corre, Y. and Y. Lostanlen, 2009).

We have developed numerical methods based on RT with coding in MATLAB software environment which are according to 2D RT calculations. The RTE is based on ray-shooting, also called ray-launching strategy (Langen, B., 1994). All geometrical details of 2D scenario are estimated the reflections and scattering due to barriers. A vertical 2D cross section of sample environment and the placing of transmitter and receiver are shown in Fig.2. As mentioned before the goal of this article is studying rough surfaces in indoors and one of the roughest surfaces is always the floor. Hence three other sides of the room i.e. two side walls and the sealing are considered as smooth surfaces.

Fig. 1: 3D plane of the indoor environment used in this study.

Fig. 2: 2D demonstration of the modelled propagation environment.

Basically, the effective amount of reflected or transmitted energy for every surface depends on the reflection and transmission factor which they themselves depend on permittivity coefficient, thickness,
roughness, polarization and the angle of electromagnetic wave incident (Sato, K., 1995). So for presenting this model in RTE it is necessary to introduce each element with different material or thickness to the software such as permittivity coefficient related to the propagations frequency, its thickness and geometry. Permittivity coefficient is a complex quantity and it is shown by \( \varepsilon \), (1) to shows the two composition of \( \varepsilon \) (He, J., 2004).

\[
\varepsilon = \varepsilon - j\varepsilon'' = \varepsilon_0\varepsilon_r - j\varepsilon_0\varepsilon_r \tan \delta.
\]

Where \( \tan \delta \), \( \varepsilon_0 \) and \( \varepsilon_r \) are respectively the loss tangent, the vacuum permittivity and the relative permittivity (also called dielectric constant). In this 2D plain we have a type of wall with 10cm thickness and associated complex permittivity of \( \varepsilon = 3.686 + j0.4 \). In this research we calculate CIR which gives accurate information about diverse rough surfaces. To develop this type of engine, we should configure initially the propagation environment with the associated materials in the applied frequency. After the configuration of the propagation environment it is necessary to determine the type and place of transmitter and receivers antennas. Then the process of ray shooting in propagation environment begins. Usually for precise propagation modeling all propagation mechanisms should be considered such as scattering, free space propagation, reflection, penetration, transmission, refraction and diffraction. The effect of diffraction in indoor environment from sharp edges and furniture is important. In this research the number of sharp edges is not significant. Thus, the effect of diffraction is negligible (Balanis, C.A., 2005). Moreover, as explain before, some phenomena like penetration, transmission and refraction has high losses because of specific propagation characteristics in 60 GHz frequency and consequently has fewer roles in calculations. Therefore, to reduce calculation complications these phenomena are excluded. So just free space propagation, scattering and reflection are applied in RTE. The free space propagation is calculated according to Friis formula, in which the received power is given by (Sato, K., 1995)

\[
p_{r}(\text{dB}) = p_{t}(\text{dB}) - 32.5 - 20 \log_{10}\left[ f(\text{GHz}) \right] - 20 \log_{10}\left[ D(\text{m}) \right] + G_{t}(\text{dB}) + G_{r}(\text{dB}).
\]

\( p_{t} \), \( f \), \( D \), \( G_{t} \) and \( G_{r} \) are respectively transmitted power, work frequency, the distance between transmitter and receiver, transmitter gain and receiver gain. Furthermore, Reflection mechanism in RTE calculates according to reflection coefficient (Chuah, C.N., 2002).

\[
\bar{R} = \frac{1 - \exp(-j2\delta)}{1 - R_{k}^{\perp} \exp(-j2\delta)} R_{k} \text{ for } k \in \{ \perp, \parallel \}
\]

Where \( \delta = \frac{2\pi d}{\lambda} \sqrt{n^2 - \sin^2 \theta} \) in which \( d \cdot \lambda \cdot \theta \), and \( n \) are the material thickness, the wavelength in free space, the angle of incident and the complex refractive index of reflecting materials, respectively. The \( R_{\perp} \), \( R_{\parallel} \) are Feresels reflection coefficients for the interface between air and the electric material while electric is perpendicular and parallel to the plane of incident, respectively. We define plane of incident as the plain including the wave propagation direction and the normal to the reflecting surface. The \( R_{\perp} \) and \( R_{\parallel} \) coefficients are calculated as following:

\[
R_{\perp} = \frac{\cos \theta - \sqrt{n^2 - \sin^2 \theta}}{\cos \theta + \sqrt{n^2 - \sin^2 \theta}}
\]

\[
R_{\parallel} = \frac{n^2 \cos \theta - \sqrt{n^2 - \sin^2 \theta}}{n^2 \cos \theta + \sqrt{n^2 - \sin^2 \theta}}
\]

Then with the help of RT method and applying above equations CIR calculates as following (Lostanlen, Y. and G. Goungeon, 2007).

\[
h(\tau) = \sum_{i=0}^{M} \sqrt{P_{i}} e^{j\phi} \cdot \delta(\tau - \tau_{i})
\]
Where $p_i$, $\theta_i$ and $\tau_i$ are the power, the phase and the delay of the ith received ray. Now, with the introduction of the place and type of transmitter and receiver antennas the effect of rough surface can be studied for electromagnetic waves scattering distribution. As show in Fig. 2, hereinafter with a few changes in one of the room surfaces that is floor; all calculations in this room could be done. According to this Fig transmitter and receiver could be placed in every spot of sample environment which in this research transmitter is located in one surface and a receiver in another. In this software environment different kinds of antenna can be enter. In calculations each antenna configures according to its gain and radiation pattern. Transmitter and receiver antennas in all accomplished researches are chosen from type isotropic and horn antenna with the 20dB gain. For presenting received power in receiver spot and reduction of calculations complexity, threshold of -150dBm is estimated because the lower amount from this are accounted as a noise. Also, For decreasing the time of calculations there is a time limitation for receiving the rays in receiver spot, which in indoors it is 800ns approximately. So, Because RPS software is capable of waves propagation modeling in smooth surface, the output of the software is an RT software is reliable, in order to verify the output of the RTE is the CIR can be compared. In Fig. 3 this comparison between RPS and RTE is shown. As it can be seen in the Fig all output of RPS for example in 6ns can be seen in RTE too. In addition there is an output for example in 22ns which is not in relevant results of RPS. In fact because of the RPS software just shows a limited number a received rays, some output of RTE are not in RPS. On the other hand because of the difference in calculation of parameters among software, here also some differences can be seen in the output domain. However almost all of these outputs are similar in both software this difference can be ignored. Therefore according to comparisons the output of RTE is reliable for modeling of propagation environment and considering all its mechanisms.

Fig. 3: Comparison results between RPS and RTE.

**Study of the effect of different statistical models on reflection pattern in CIR:**

As mentioned before because of waves propagation software are considering the electromagnetic wave just as a ray and not as a surface wave their output of the CIR is not continuous and discrete output. There are two ways to improve this output that arises from the lack of a precise description of propagation environment (Tsang, L., 2012). One is to send countless rays with very high accuracy which is not explainable from time aspect. The second solution is to consider the effective parts. One of these effective parts in wave propagation software is the roughness effect. We want to see with Considering the rough surfaces what changes can be seen in impulse response. In this section the roughness of different surfaces are shown by placing statistical distributions. In fact here one of the side of propagation environment in RTE which is floor are considered in a way that when wave incident to it reflect according to statistical distributions not as a specular reflection. For this reason different statistical distributions are placed in one of propagation environments surfaces (simulated floor in RTE).

According to accomplished research in the past propagation patterns can be modeled by standard statistical distributions. Due to these distributions have specific mathematical functions can be easily applied in numerical simulating of propagation channel and also in wave propagation software. Therefore in the section uniform, Gaussian and exponential statistical distributions are discussed and implementation details of each of them in RTE follows.

**The implementation method of statistical of distributions in RTE:**

According to Fig. 4 which is a vertical 2D cross section of a room in RTE, when the ray with the power of $p$ and the angle of $\theta$ incident the floor, according to a statistical distribution it reflects as a power. In this Fig $\theta_1, \theta_2, \theta_3, \theta_4$ and $\theta_5$ are equal $\theta-10, \theta-5, \theta, \theta+5$ and $\theta+10$ respectively.
Fig. 4: The implementation method of statistical of distributions in RTE.

**Uniform distribution:**
According to Fig. 5 which shows the probability density function due to uniform distribution of power in different $\theta$ power reflects as a uniform distribution when each time the ray incident to the floor.

**Gaussian distribution:**
To study the effect of placing a Gaussian distribution in impulse response, according to Fig. 6, each time the ray incident to the floor is considered as the reflect of a Gaussian distribution based on calculated power.

**Exponential distribution:**
Like prior actions as it shown in Fig. 7 which is probability density function for exponential statistical distribution, in this part the effect of an exponential distribution RTE studies.

Fig. 5: Probability density function of uniform distribution in RTE.

Fig. 6: Probability density function of Gaussian distribution in RTE.
**Geometrical modeling of random rough surface:**

In electromagnetic wave scattering issue for rough surface geometrical specifications play a vital role. There was always a challenge the ability of characterization a random rough surface by the means of some parameters in a wide frequency band. However, if the geometrical specification of random rough surface is not correct the results would not be reliable even they are obtain from exact mathematical solutions. Also, if Monte Carlo simulations is applied, the geometrical characterization of surfaces is still needed (Tsang, L., 2000).

Totally almost all natural surfaces have ups and downs, which this roughness is controlled by root mean square (rms) heights and its amount is near the wave length in work frequency. Here because of the work frequency in 60 GHz this amount is about 5mm. there is another type of rough surface which is in bigger scale that ups and downs are changing gradually. Here we focus just on the first type which affects millimeter wave scattering. Consider a single dimensional rough surface with height function $z = f(x)$, which is a Gaussian random process. The Gaussian process are characterized by a correlation function in general (Tsang, L., 2001):

$$\langle f(x_1) f(x_2) \rangle = h^2 C(x_1, x_2)$$

which C and h are the note correlation function and rms height, respectively. If height functions are statistically translational invariant, then we have $C(x_1, x_2) = C(x_1 - x_2)$. The Fourier transform from $h^2 C(x)$ results $W(k_x)$ as a power spectral density power. A surface of limit size $L$ is to be generated from the power spectral density. We make $f(x)$ periodic outside $L$, i.e., $f(x) = f(x + L)$. Fourier series for represent is $f(x)$ as following (Tsang, L.C., 1995):

$$f(x) = \frac{1}{L} \sum_{n=-\infty}^{\infty} b_n e^{(2\pi n x/L)}$$

Where $b_n = 2\pi LW(k_x) r$ and $k_x = \frac{2\pi n}{L}$. Usually there are two correlation functions for modeling random rough surface: 1) The Gaussian Correlation function:

$$C(x) = \exp\left(-\frac{x^2}{L_x}\right)$$

and 2) the exponential correlation function:

$$C(x) = \exp\left(-\frac{|x|}{L_e}\right)$$

In (7) and (8), $L_x$ is the correlation length in X-direction. The power spectral density Corresponding to the Gaussian correlation function is as following:

$$W(k_x) = \frac{h^2 L_x}{2\sqrt{\pi}} \exp\left(-k_x^2 L_x^2\right)$$

and for the exponential correlation function:
In Fig. 8 Gaussian rough surfaces with Gaussian and exponential correlation functions are compared.

\[ W(k_x) = \frac{h^2}{\pi(1 + k_x^2L_s^2)} \]  \hspace{1cm} (11)

Fig. 8: Random rough surface profile with Gaussian and exponential correlation functions.

Random rough surface Scattering were originally modeled in Monte carlo simulations by Gaussian correlation functions (Chan, C.H. and L. Tsang, 1995; Pak, K., 1997; Tran, P. and A. Maradudin, 1994; Torrungrueng, D., 2000; Oh, Y., 1992). Random rough surfaces profiles are measured from them and correlation functions are obtained. From these measurements concluded that using exponential correlations function is much better. Because they have fine scale structures and the surfaces that uses this function has more irregularities rather than Gaussian correlation function and the results have better agreement with experimental measurements (Geng, S., 2009).

Implementation of random rough surface in RTE and the finding method of scattering distribution:

First we make a one dimensional Gaussian random rough surface by exponential correlation function based on mentioned equation. Here the reason we use a one dimensional rough surface is that we only look for roughness in one side of the room which is the floor. For finding scattering distribution due to an electromagnetic wave incident to this surface, it should be interred in RTE environment as shown in Fig. 9. In this mode, when wave incident to the rough surface it reflects its energy in just one direction and it differs when it incident to an even surface which makes different trajectories. Because, this surface has an angle to the horizon and also has random slopes. Now for studying the effect of roughness and consequently obtaining the scattering distribution we need to simulate a very rough surface. Because of the high volume calculation in RTE, this job takes a lot of time. So considering these circumstances instead of getting RTE output which channel impulse response is, we obtains statistical distribution of rough surface according to random slops that is due to of different surfaces in horizon. Then we will studying that they are similar with reach of the other prior scattering distribution function. For this reason according to the angle of electromagnetic wave impact transmitted by the antenna in RTE to specified incident spot on rough surface where here is \( x = 0 \) we get the slop of random rough surface which it is random itself. In Fig. 9 this slop I shown by the angle \( \theta \), which is related to the incident angle too.

Studying the effect of one reflection statistical model due to different angles in CIR:

So far we have researched the surface roughness first by placing different distribution and then by the random rough surface itself. In this part the target is to study the effect of roughness made by one reflection statistical model from different angles in CIR till now the effect of distributions are studied as a roughness representative. In fact in this section these distribution are used only as statistical not as a model. Therefore here roughness in RTE will determine in two methods.

For this reason as shown in Fig. 10, the rough surface in RTE determines so that collided electromagnetic waves are reflected with different angle instead of the same angle, in fact these angles are considered with two methods and completely random with \( x \) specified distances which in every distance wave reflect in different angle in comparison with the incident angle. In the first method, when the electromagnetic wave incident to the rough surface with the angle \( \Theta \) and the specified distance \( x \) the angle of its reflection is made with random number and to be quite uniform from 0 to 90 degree. And then in second method these angles are considered so
that in incident of electromagnetic waves to the simulated floor in RTE, it reflects according to a Gaussian one reflection statistical model which is again random.

As it can be seen in this Fig transmitted wave by the transmitter antenna after colliding to the floor in each \( X \) distance where here is 20cm, it reflects with different angles comparing to collision angle.

**Experimental studies:**

A lot of experimental studies on propagation in 60 GHz frequency have been done. so far, diverse aspect of 60 GHz propagation channel has considered in these measurements (Manabe, T., 1995; Yang, H., 2005; Collonge, S., 2004; Anderson, C.R. and T.S. Rappaport, 2004; Kivinen, J., 2007; Zwick, T., 2005). All of these results are effective for improving the design channel model in simulating radio systems in this frequency band. These modeling methods can be categorized in three groups: algebraic, semi algebraic and experimental. In algebraic modeling like ray tracing methods, the results are very close to measurements on high frequencies, e.g., MMW applications. As we know in this modeling’s electromagnetic specifications of propagation environment should be determined completely and precisely. On the other hand knowing the electromagnetic characteristics of materials used in the indoor structure is essential. Hence the research of scattering distribution of experimental surfaces and finding its statistical distribution are considered as an important phenomenon in measurements. Also, Because of all these models are based on experimental method, there should be broad measurements by great amount of information in different environments. There are limited researches that has been done over the subject and most of them related to characteristics of reflection and transmission from building materials in 60 GHz frequency and nothing has been done on rough surfaces scattering and (Correa, L.M. and P.O. Frances, 1994; Hashimoto, O., 1999; Sato, K., 1997). The authors in studied reflection, transmission and also permittivity coefficients for different type of flooring and for 57-64 GHZ frequencies. In fact the goal of experimental studies is to find complex permittivity coefficient for flooring materials by the means of reflection coefficient measurement. While in this research the goal is to study scattering pattern of
electromagnetic waves from rough surfaces. In both researches one type of measurements system is apply and the materials are the same.

**Measurement structure:**

Considered measurement structure in this article which has ability of measuring in 60 GHz frequency is shown in Fig.11. By using this structure we study the scattering pattern in two modes, TE and TM it means the time that electric field and magnetic field are not existed in the propagation direction.

To avoid receiving a dominant direct wave by the receiving antenna from the transmitting antenna when the incident angle is large, and the mutual coupling effect between the transmitting and receiving antennas when the incident angle is small, the incident angle is restricted between 10° and 65° with 5° resolution. The house flooring samples considered in this article are classified into three groups: finished- flooring materials, subfloorings, and underlayments.

The types of flooring that is used in this article are listed in Table 1 according to the placing. The result of this experimental study is shown in a similar Table.

![Fig. 11: Schematic of the measurement setup.](image)

**Fig. 11:** Schematic of the measurement setup.

<table>
<thead>
<tr>
<th>Table 1: Materials Under The test According To The Placing.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut and loop pile carpets</td>
</tr>
<tr>
<td>Laminate</td>
</tr>
<tr>
<td>Vinyl</td>
</tr>
<tr>
<td>Underpad</td>
</tr>
<tr>
<td>MDF</td>
</tr>
<tr>
<td>Chipboard</td>
</tr>
<tr>
<td>Plywood</td>
</tr>
</tbody>
</table>

**The result of numerical simulating and measurements:**

In this section we show the result of channel impulse response and also scattering distribution which is based on applying of different types of rough surfaces in integrated RTE software. Because as explained above to reach to precise propagation channel model and similar to the measurements, all propagations mechanism especially scattering should be consider. we also show the experimental result of applied different floorings to reach the scattering patterns.

**The effect of different statistical models on reflection pattern in channel impulse response:**

Fig. 12, 13 and 14 show results channel impulse response due to implementation of uniform, Gaussian and exponential statistical distribution, respectively. In this Figures the result of RTE are compared with two situations, smooth and also rough because of putting different statistical distributions. As it is shown in these Figures in all modes when the ray reaches to the receiver without incident to the rough surface that is the floor, the results are the same for both smooth and rough situations. but when the ray incident to the floor in all distributions the power reduces according to applied distribution and also the times ray incident to the floor. For example, in Fig. 12 as it can be seen, in 4ns results are the same for both situation. But when the ray incident to the floor for example, in 17ns according to applied uniform distribution the power has been decreased 6.9dB in
comparison with situation smooth surface. Because in that situation the ray is only once has incident to the floor. The effect due to implementation statistical distributions as roughness representative, in order to fills empty spaces the discrete Charts in Gaussian distribution is better than uniform and exponential distributions. As can be seen in uniform, Gaussian and exponential distributions we have 42, 62 and 43 received rays in output, respectively. As expected, with the consideration the statistical distributions of empty space in charts only at certain intervals of time filled. For example, in the time period between 30–35ns. Because in these implementations we have considered one of the surfaces as a rough surface.

![Fig. 12: CIR due to implementation of uniform statistical distribution in RTE.](image1)

![Fig. 13: CIR due to implementation of Gaussian statistical distribution in RTE.](image2)

![Fig. 14: CIR due to implementation of exponential statistical distribution in RTE.](image3)

**Scattering distribution of random rough surfaces:**

As mentioned before to find the scattering distribution of random rough surfaces in RTE there is a need to simulate plenty of rough surfaces. Therefore here scattering distribution due to electromagnetic wave incident to 1000 random rough surface is obtained. As it can be seen in Fig. 15, this distribution is similar to the Gaussian distribution.

In fact when the number of random rough surfaces in RTE becomes greater, scattering distribution of these surfaces is more similar to the Gaussian distribution. Therefore mathematical model resulted from scattering distribution of random rough surface calculates as following.
\[ y = a \exp\left(-\frac{(x - \mu)^2}{\sigma^2}\right) \]  

(12)

Where \( a, \mu \) and \( \sigma^2 \) are respectively the domain and constant, the average and the variance.

The effect of one reflection statistical model due to different angle in CIR:

To study the effect of this kind of roughness on CIR accurately, two methods are compared. In the first method the reflection angles of electromagnetic wave incident to the floor are made, randomly and to be quite uniform from 0 to 90 degree. In second method the angles are made randomly but according to a Gaussian distribution. Like the other ways of roughness making, the channel impulse response is studied in both smooth and rough floors in two different ranges from \( x \). Figs. 16 and 17 are shown the CIR for the first and second method, respectively. In this mode the distance between X’s is 10cm. The Figs 18 and 19 also show the CIR for the first and second methods, while in this mode the distance between X’s is 20cm. Noticing to these figures it can be observe that again the results for situation that electromagnetic wave do not incident to the rough surface is the same for both. It can also be found when the ray incident to the rough surface of the floor the received power is decreased in comparison with the situation that the floor is even. From comparing the methods of roughness making it can be found that in second way CIR has changed. For example, in mode that the distance between X’s is 10cm CIR has changed in 24ns in second method. Or in the mode that the amount is 20cm CIR has changed in 36ns in second method. This shows that using the second methods is more effective on CIR and feels the gap between responses, approximately.

Measurements results:

In this section the result of measurements are obtained for different types of flooring in two modes of TE and TM. Then according to measurement pattern the results get from statistical modeling and also statistical parameters are approximated. For this reason here the results are correspondent with standard statistical distribution like uniform, exponential, normal logarithmic and Gaussian. Figs 20 and 21 respectively show the result of scattering patterns from measurements for chipboard flooring in two modes TE and TM. As the results shown Gaussian distribution corresponds closer to them. Therefore its statistical distribution is a Gaussian
distribution and can be calculated by the (12) which is the second order and it is the result of linear sum of two Gaussian distribution.

**Fig. 17:** CIR for the second method with the distance between X’s is 10cm.

**Fig. 18:** CIR for the first method with the distance between X’s is 20cm.

**Fig. 19:** CIR for the second method with the distance between X’s is 20cm.
\[ y = a_1 \exp \left( -\frac{(x-b_1)}{c_1} \right) + a_2 \exp \left( -\frac{(x-b_2)}{c_2} \right) \]  \hspace{1cm} (13)

Where \( a_1, a_2 \) are the domain and constant, \( c_1, c_2 \) the standard deviation and \( b_1, b_2 \) the average. Statistical parameters result from different types of flooring is approximated according to table 2.

Table 2: Statistical Parameters Estimated For Flooring

<table>
<thead>
<tr>
<th>Sample material</th>
<th>Cut-pile carpet</th>
<th>Loop-pile carpet</th>
<th>Laminate</th>
<th>Vinyl</th>
<th>Underpad</th>
<th>MDF</th>
<th>Chipboard</th>
<th>Plywood</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>TE</td>
<td>0.77</td>
<td>0.76</td>
<td>0.62</td>
<td>0.39</td>
<td>---</td>
<td>0.72</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>0.76</td>
<td>0.76</td>
<td>0.99</td>
<td>0.94</td>
<td>0.79</td>
<td>0.74</td>
<td>0.91</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>TE</td>
<td>0.25</td>
<td>0.24</td>
<td>0.39</td>
<td>0.84</td>
<td>---</td>
<td>0.27</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>0.26</td>
<td>0.32</td>
<td>0.28</td>
<td>2.15</td>
<td>0.24</td>
<td>0.26</td>
<td>0.14</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>TE</td>
<td>35.7</td>
<td>38.6</td>
<td>39.1</td>
<td>52.9</td>
<td>50.8</td>
<td>40.1</td>
<td>44.5</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>39.6</td>
<td>44.6</td>
<td>43.1</td>
<td>48.7</td>
<td>50.8</td>
<td>40.1</td>
<td>44.6</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>TE</td>
<td>42.7</td>
<td>42.7</td>
<td>37.5</td>
<td>38.5</td>
<td>43.9</td>
<td>35.7</td>
<td>55.7</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>42.7</td>
<td>80.7</td>
<td>56.4</td>
<td>42.6</td>
<td>29.8</td>
<td>44.0</td>
<td>55.7</td>
</tr>
<tr>
<td>( c_1 )</td>
<td>TE</td>
<td>4.1</td>
<td>12.1</td>
<td>6.06</td>
<td>7.74</td>
<td>---</td>
<td>16.5</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>10.1</td>
<td>18.1</td>
<td>16.1</td>
<td>16.1</td>
<td>10.3</td>
<td>16.4</td>
<td>17.1</td>
</tr>
<tr>
<td>( c_2 )</td>
<td>TE</td>
<td>75.6</td>
<td>75.1</td>
<td>44.8</td>
<td>25.2</td>
<td>---</td>
<td>38.1</td>
<td>76.1</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>75.1</td>
<td>76.1</td>
<td>30.1</td>
<td>40.4</td>
<td>69.9</td>
<td>37.9</td>
<td>76.2</td>
</tr>
</tbody>
</table>

As can see in these table these parameters for all floorings excepts for the underpad in TE mode and plywood in TM mode are approximated. as their scattering pattern are shown in Figs. 22 and 23 respectively, which are completely random and are not corresponded on any statistical distribution. In table 3 also based on mean secure error (MSE) which extracted from MATLAB software, the difference between measured pattern and modeled by Gaussian distribution is shown. As it can be observed in this table these errors are existed in all floorings except underpad and plywood which only in one mode this amount is gained according to the pattern of their scattering distribution measurement.

![Fig. 20: Measured scattering pattern chipboard flooring in TE mode.](image)

![Fig. 21: Measured scattering pattern chipboard flooring in TM mode.](image)
Table 3: Error Rate Is Measured And Modeled Patterns With The Criteria Of Mse.

<table>
<thead>
<tr>
<th>Sample material</th>
<th>TE</th>
<th>TM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-pile carpet</td>
<td>0.0002256</td>
<td>0.0003462</td>
</tr>
<tr>
<td>Loop-pile carpet</td>
<td>0.0002283</td>
<td>0.0003984</td>
</tr>
<tr>
<td>Laminate</td>
<td>0.0002917</td>
<td>0.0003897</td>
</tr>
<tr>
<td>MDF</td>
<td>0.0002693</td>
<td>0.0003354</td>
</tr>
<tr>
<td>Vinyl</td>
<td>0.0003611</td>
<td>0.0002559</td>
</tr>
<tr>
<td>Chipboard</td>
<td>0.0003149</td>
<td>0.0002965</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.0003874</td>
<td>0.0002479</td>
</tr>
<tr>
<td>Underpad</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 22: Measured scattering pattern underpad flooring in TE mode.

Fig. 23: Measured scattering pattern plywood flooring in TM mode.

Conclusion:

The objective of this study is to investigate scattering electromagnetic waves, against rough surfaces, to improve ray tracing based numerical modeling of propagation channel. Study behavior of electromagnetic wave propagation from rough surfaces are essential. In typical radio waves propagation softwares, such as RPS only, reflection, transmission, refraction and diffraction are considered. In fact They do not include in the scattering from rough surfaces. Thus, an integrated platform is required to represent all the components. To realize such a platform, a tool for modeling the propagation environment as RTE in the MATLAB software environment is presented. Because, In propagation channel modeling introducing a complete propagation wave pattern with its all factors such as reflection, transmission, refraction, diffraction and scattering as a consolidated software environment can present results competing with the experimental measurements. more concentrate on the major aim of this study, owing to particularly propagation properties in 60GHz band, for modeling propagation channel of the mentioned frequency is selected. So, to study wave propagation, it considered one room with specified dimensions in RTE as a propagation environment.

After the introducing propagation environment in the RTE, rugged topography by three different texture. In all these a threshold configured for the received power and the reaching time of the ray to the receiver. We investigate the propagation mechanism in several steps. First, using different statistical distributions. Then, by the putting statistical models of single reflection from different angles. Finally, by random rough surfaces through statistical process is created. Also, effect placing each of them in the CIR is studied. In type 1 roughness placing of different statistical distributions showed that Gaussian statistical distribution is better in feeling of empty gaps. In type 2 roughnesses scattering distribution due to the impact of electromagnetic wave to a random rough surface studied and the results showed that Gaussian statistical distribution which is used in type 1 is closer to the existed roughness in geometrical surfaces and consequently its impulse response is more reliable. Finally, in type 3 roughness one reflection patterns for introducing roughness in specified distances of
floor made by two distinguished way. In the first method the reflection angles selected randomly and uniformly between of 0 to 90 degree. In the second method, this angles were random again but according to Gaussian distribution and in a direction has been reflected. The result shows that using of distributions statistically not only affects the CIR, but also in second method feels the empty spaces. A continues Wave (CW) transmit-receive measurement setup with measuring possibility of 60GHz frequency band to find the scattering pattern of home flooring and also, validating the results of the simulations is employed. Then their statistical distribution and mean values and variance gained for all floorings. Their results show that the scattering distribution of random rough surface simulating is closer to the measurements. Theoretical and experimental results of the project is led to introduce of statistical and mathematical models for wave scattering pattern on the rough surface. In addition, the obtained results are applicable not only for the designers of MMW systems for optimization a transmitter-receiver, but also for channel modeling software based on ray tracing.

As a research here we present some recommendation to continue this study: Research in more sample frequencies and in 57-64 GHz frequency bands. Study on other surfaces’ scattering distribution that is except floors. Considering FDTD numerical methods in comparison with function of presented method. Application in low band frequency of communication and to consider plot errors. Finally, Research in satellite communication applications and remote sensing.

REFERENCES


