On the Influence of Diffuse Scattering on Multiple-Plateau Diffraction Analysis at mm-Wave Frequencies

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***Abstract*— A study of the impact of the diffuse scattering phenomenon when calculating radiowave multiple-plateau diffraction losses at mm-wave frequencies is hereby presented. In this sense, measurements of the total attenuation caused by a series of either rough or polished brick blocks are properly compared with the theoretical multiple-diffraction losses of an array of ideally-smooth brick blocks predicted by a hybrid uniform theory of diffraction-physical optics (UTD-PO) formulation. The results show the influence of diffuse scattering phenomena when it comes to calculating radiowave multiple-plateau diffraction attenuation, and can be applied to the obtaining of more realistic mm-wave propagation models when multiple-diffraction over rectangular obstacles with irregular (rough) surfaces has to be considered.**

***Index Terms*— Multiple-diffraction, diffuse scattering, millimeter-wave band, UTD, rectangular obstacles.**

I. Introduction

THE analysis of radiowave multiple-diffraction caused by an array of obstacles modeled by rectangular shapes (*plateaux*) has been carried out by a great deal of formulations either based on the uniform theory of diffraction (UTD) [1], the parabolic equation method [2], or a hybrid UTD-physical optics (PO) approach [3]. On the other hand, the mm-wave frequency band has become a very promising option for the forthcoming high-throughput wireless telecommunication systems due to the large bandwidth available [4] and the small frequency reuse distance offered [5]. In this sense, several works regarding the analysis of radiowave diffraction at mm and sub-mm-wave frequencies have been recently published [6]-[8], where the rectangular-shaped diffracting obstacles are always considered to bear perfectly smooth surfaces. However, when it comes to calculating multiple-diffraction losses caused by *plateaux* with irregular (rough) surfaces, an additional analysis of the so-called "diffuse scattering" (phenomenon by which waves impinging over surfaces with irregularities are scattered in other than the specular direction) appears to be necessary in order to obtain accurate results. In this sense, the electromagnetic field

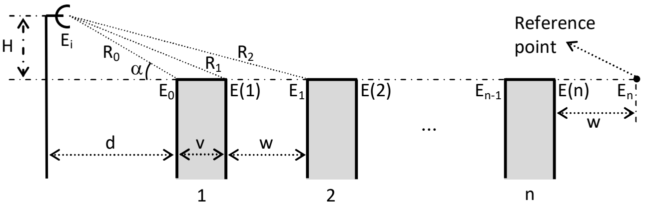

Fig.1. Scheme of the propagation environment considered when ideally-smooth blocks are assumed for the theoretical UTD-PO prediction.

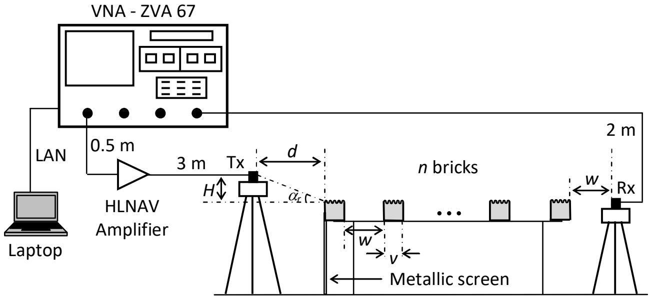

Fig. 2. Scheme of the measurement setup.

diffraction by a single knife edge with random roughness was analyzed in [9] but still the incorporation of multiple and more complex obstacles seems to be needed. Moreover, such consideration could be especially important at mm-wave frequencies, where the irregularities existing at the surface of the diffracting obstacles may be of the same order of magnitude as the wavelength.

Diffuse scattering has been widely analyzed regarding both urban and indoor radio propagation [10]-[12]. However, to the best of the authors' knowledge, there has not been any published work in which the impact of diffuse scattering on multiple-diffraction attenuation calculation is studied. Therefore, in this paper, such possible impact is analyzed at mm-wave frequencies through measurements performed at 60 GHz to obtain the total attenuation—relative to the free-space field strength—caused by a series of either rough or polished rectangular brick blocks, and the subsequent comparison of the

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measured results with the theoretical multiple-diffraction attenuation of an array of ideally-smooth brick blocks predicted by a hybrid UTD-PO formulation. In this sense, it should be noted that the empirical results shown in this work have been performed within a laboratory context. This way, as shown in [13], this type of measurements undertaken under laboratory conditions –on either scaled or real models– present the advantage that they are performed in a controlled environment (so that all parameters of the scenario are known) while at the same time providing knowledge that can be applied to a realistic problem of radio propagation. This could be the case of an indoor horizontal-plane analysis of a micro/nano-cell –or a *hot-spot*– where the transmitter is surrounded by brick walls/columns.

II. Theoretical Model

In order to obtain the theoretical multiple-diffraction attenuation prediction, the scheme of the propagation environment considered can be observed in Fig. 1, where n finitely conducting rectangular *plateaux*—with a flat top—of the same height, which is relative to the transmitter antenna height H, have been taken into account. The blocks are assumed to bear the same thickness v and constant inter-*plateau* spacing w. Furthermore, the transmitting point can be located above or level with the average block height ($H\geq 0$) and at a certain distance d from the array of obstacles (spherical-wave incidence).

In this way, the total field arriving at the reference point indicated in Fig. 1 can be calculated, at a frequency of 60 GHz, by applying the final UTD-PO formulation proposed by the authors in [7].

III. Measurement Setup

In Fig. 2, a schematic of the measurement setup considered is shown. The same measurement setup was taken into account in [7][14][15] but, in this case, an array of either rough or polished brick blocks were assumed (an example of these brick blocks is shown in Fig. 4 and Fig. 5, respectively). Morever, as opposed to [14], the gain of the antennas ranges from 3.6 to 5.3 dBi and the considered frequency band is 55 to 65 GHz. Furthermore, in this work, two measurement campaigns were carried out. In the first, both rough and polished bricks as well as n=3, w=23.55 cm, v=5.1 cm, d=20 cm, and both *soft*/horizontal and *hard*/vertical polarizations were considered. On the other hand, contrary to [14], the transmitting antenna height H was varied from 0 m to 0.015 m in steps of 0.001 m (16 positions), and each position was measured 28 times (in order to minimize thermal AWGN noise and to check the consistence of data), obtaining the average attenuation —relative to the free-space field strength—for every value of H. Therefore, the incident angle α bears a maximum value of 4.29°, which is appropriate for multiple-diffraction considerations. Regarding the second measurement campaign, the same set of parameters used in the first was assumed but, in this case, a fixed value of H=0.0075 m was considered, and now the parameter d was varied from 0.20 to 0.70 m in steps of 0.05 m (11 positions). Moreover, in both cases, the number of frequency points over which the channel frequency response was measured was 1024, with equal spacing between 57 and 66 GHz.

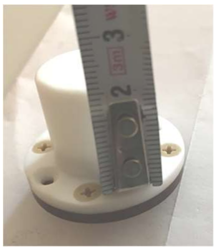

Fig. 3. Antennas used in the measurements.

Fig. 4. Example of the rough brick blocks considered.

Fig. 5. Example of the polished brick blocks considered.

The antennas considered for the measurements are Q-par QOM55-65 VRA 55 to 65 GHz omni-directional V-type antennas (Fig. 3). In this sense, it should be mentioned that this work has been carried out assuming a far-field characterization since, as observed in Fig. 3, the maximum dimension of the antennas is D<2 cm; therefore, the far-field starts at a distance $2D^2/\lambda$ [16][17], which is 16 cm, and, as previously stated, the minimum distance between the transmitter and the first brick considered in this paper is 20 cm. The power transmitted by the Vector Network Analyzer (VNA) was set to 0 dBm, so that a dynamic range of more than 100 dB at 60 GHz was achieved. In such a way, the resolution time obtained was of 0.11 ns (0.03 m) and the time-gating technique which is explained in [7] was properly applied. This technique allows for the selection of the multiple-diffraction contributions (which are used to estimate the relative attenuation), while at the same time removing the rest of contributions (undesired). Finally, since the number of frequency points selected was 1024, a maximum delay of 11.37 µs (34 m) could be measured, without time aliasing in the domain (as in [14], the maximum dimension of the measurement environment was 7 m).

IV. Measurement of the Roughness of the Bricks

In order to characterize a sample of both polished and rough brick, their roughness was properly measured by means of a Talysurf CLI optical profiler. In this way, roughness values, surface topography images and cross-sectional profiles were achieved. In Fig. 6 and Fig. 7, the scanned heights of the polished brick sample and the rough brick sample, respectively, are shown. Moreover, in Fig. 8, the average cross-sectional profile of both materials can be observed. In order to thoroughly quantify the roughness of a specific material, it should be said that the so-called roughness parameter Ra of the standard ISO 4287 is usually used, being the most universally used roughness parameter for general quality control [18]. Such parameter can be defined as the arithmetical mean deviation of the obtained profile. In Table 1, the *Ra* parameter is depicted for the two kinds of bricks employed in the measurements.

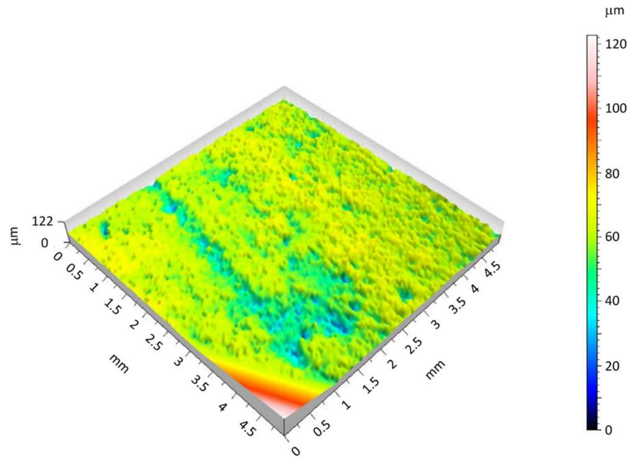

Fig. 6. Scanned heights of the polished brick sample.

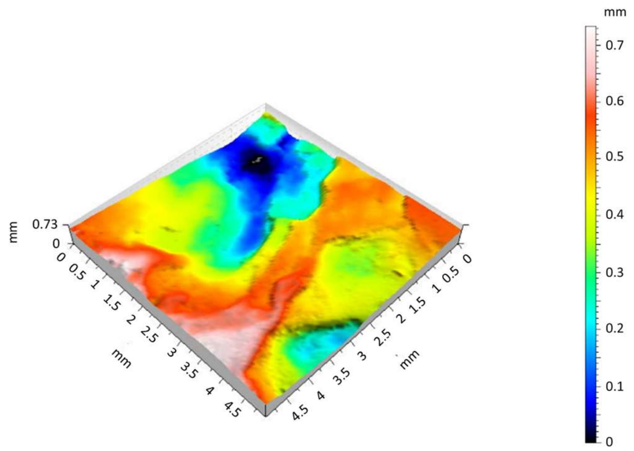

Fig. 7. Scanned heights of the rough brick sample.

TABLE I
ROUGHNESS PARAMETER VALUES

Material	Ra roughness parameter (µm)			
	Mean	**Std. dev.**	**Min.**	**Max.**
Polished Brick	3.08	0.4689	2.046	4.908
Rough Brick	12.02	2.304	8.763	20.09

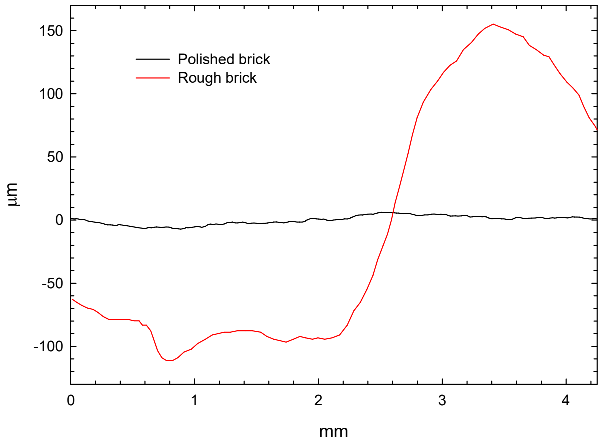

Fig. 8. Average cross-sectional profiles of polished and rough brick samples.

The higher the roughness of the material, the higher the scattered energy; usually, the diffuse scattering models include a parameter that is related to the mentioned energy. In this way, the three diffuse scattering sub-models developed in [11], derived from the Effective Roughness model, define the parameter *S*, which controls the percentage of the energy of the impinging wave that is spread in all directions. As shown in [19], the rough brick bears a scattering parameter *S* between 0.3 and 0.5, and the polished brick is assumed to show values of *S* between 0.1 and 0.2.

V. Results

In Fig. 9 and Fig. 10, the results for the attenuation as a function of *H* at the reference point of Fig. 1—relative to the free-space field strength—calculated with the UTD-PO formulation for n=3 (three rows of rectangular ideally smooth bricks with a complex permittivity of 6.3–0.35j at 60 GHz [20]) are compared with the measurements performed at 60 GHz, considering both polished and rough bricks, w=23.55 cm, v=5.1 cm, d=20 cm, and both *soft*/horizontal and *hard*/vertical polarizations, respectively.

Regarding the trend of the results, we could say, as a general comment, that the attenuation decreases with H due to the fact that the angle of incidence over the obstacles increases, and therefore the presence of the diffracting elements within the first Fresnel zone of the wave is progressively less significant (clearance is greater), blocking less energy and leading to a smaller attenuation.

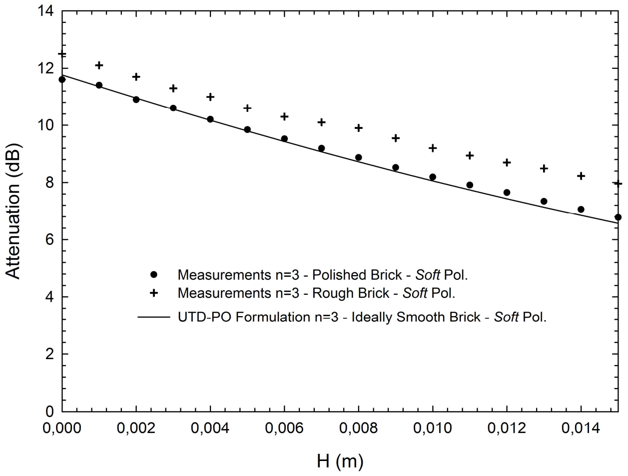

Fig. 9. Comparison of the attenuation results, at 60 GHz, for ideally smooth bricks with the measurements (considering both polished and rough bricks). n=3, d = 20 cm, w = 23.55 cm, v = 5.1 cm, and *soft/horizontal* polarization.

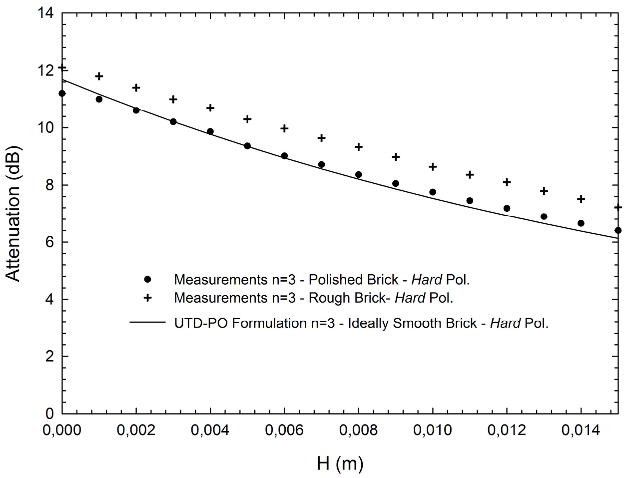

Fig. 10. Comparison of the attenuation results, at 60 GHz, for ideally smooth bricks with the measurements (considering both polished and rough bricks). n=3, d = 20 cm, w = 23.55 cm, v = 5.1 cm, and *hard/vertical* polarization.

On the other hand, as can be observed, there exists, for both polarizations, a good agreement, when the smallest angles of incidence are considered, between the theoretical prediction for ideallysmooth bricks and the measured results for polished bricks. However, as the angle of incidence over the bricks increases (H increases), the polished bricks progressively show slightly more attenuation than the theoretical results for perfectly flat bricks. This is due to the fact that, although the former have been polished, they bear a diffuse scattering parameter S of 0.1-0.2 (as mentioned in Section 3) which leads to a progressively greater additional attenuation, due to diffuse scattering, as the wave impinges with greater angles of incidence over the blocks (rays bounce back in arbitrary directions in a more relevant way). This fact is in agreement with the results shown in [9], where the electromagnetic field diffraction by a knife edge with random roughness is analyzed. On the other hand, the measured results for rough bricks (S of 0.3-0.5) show significantly more attenuation than the theoretical prediction for ideally smooth bricks (up to 1.39 dB more for *soft* polarization and up to 1.17 dB more for *hard* polarization) and, again, such difference increases as greater angles of incidence are considered (the attenuation due to the phenomenon of diffuse scattering gets more relevant). All in all, it should be said that, according to the Rayleigh criterion, in order to fully explain the obtained results, there should be considered the possibility of an additional phenomenon regarding mm-scale inhomogeneities in the material composition of the bricks that is also contributing to the *scattering*. In fact, such phenomenon would also become more noticeable at greater angles of incidence.

In Fig. 11 and Fig. 12, the results for the attenuation as a function of d—relative to the free-space field strength—calculated with the UTD-PO formulation, for n=3, are compared with the measurements performed at 60 GHz for polished and rough bricks, w=23.55 cm, v=5.1 cm, H=0.0075 m, and both *soft*/horizontal and *hard*/vertical polarizations, respectively.

As can be seen, again, a good agreement between the theoretical prediction for ideally smooth bricks and the measured results for polished bricks is observed for both polarizations, with such polished bricks slightly showing more attenuation than the theoretical results as the angle of incidence over the bricks increases (d decreases). Moreover, the measured results for rough bricks show again more attenuation than the theoretical prediction for ideally smooth bricks (up to 1.15 dB more for *soft* polarization and up to 1.1 dB more for *hard* polarization) and such difference increases in general as greater angles of incidence are considered (smaller values of d). Finally, it should be noted that when d increases from the smallest value (d=0.20 m), at first, the attenuation decreases due to the fact that the spherical incidence tends towards a plane-wave (see [21]) but then, at a certain point, since H is fixed, the fact that the angle of incidence is progressively smaller –which leads to higher multiple-diffraction losses– has a greater impact than the previous tendency, resulting in a growing attenuation.

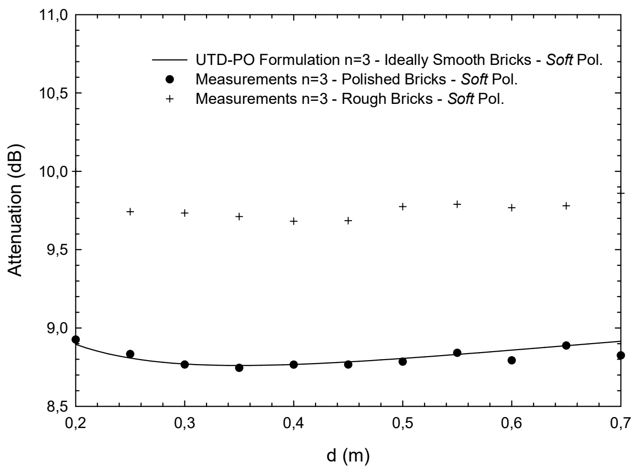

Fig. 11. Comparison of the attenuation results, at 60 GHz, for ideally smooth bricks with the measurements (considering both polished and rough bricks). n=3, H = 0.0075 m, w = 23.55 cm, v = 5.1 cm, and *soft/horizontal* polarization.

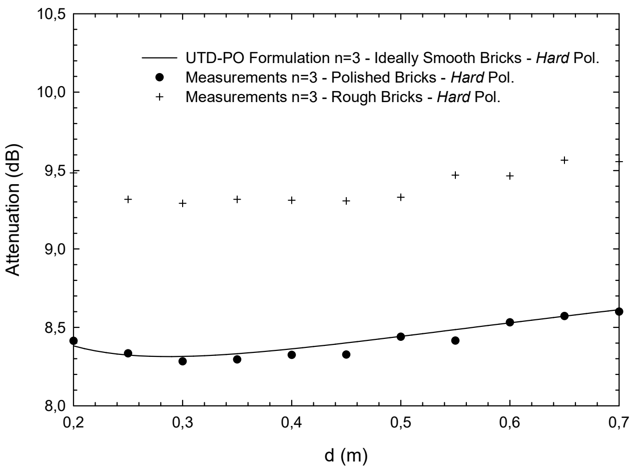

Fig. 12. Comparison of the attenuation results, at 60 GHz, for ideally smooth bricks with the measurements (considering both polished and rough bricks). n=3, H = 0.0075 m, w = 23.55 cm, v = 5.1 cm, and *hard/vertical* polarization.

VI. Conclusions

The influence of the diffuse scattering phenomenon when calculating radiowave multiple-plateau diffraction losses at the mm-wave frequency band has been analyzed. The theoretical UTD-PO prediction for multiple-diffraction attenuation caused by a series of ideally smooth bricks has been compared with measured results regarding an array of both polished and rough blocks of brick. While solid agreement is found, when assuming small angles of incidence, for both polarizations, between the theoretical values and the measurements results performed with the polished bricks, the latter progressively show slightly more attenuation as the angle of incidence over the blocks increases, due to the greater impact of the diffuse scattering. Moreover, the measured results regarding the rough bricks offer significantly more attenuation than the simulated values with flat blocks (up to 1.39 dB more for *soft* polarization and up to 1.17 dB more for *hard* polarization with the campaign varying H, and up to 1.15 dB more for *soft* polarization and 1.1 dB more for *hard* polarization, with the campaign varying d) and, again, such difference is more pronounced as larger angles of incidence are considered, since the effect of the diffuse scattering is therefore more intense. In any case, if the degree of roughness of construction materials or rooftops is higher than that considered in this work (which implies a greater diffuse scattering parameter S), it is expected that the attenuation due to diffuse scattering increases.

Therefore, the results show that a proper consideration of the diffuse scattering phenomenon when calculating multiple-diffraction losses over rough rectangular obstacles can be essential to obtain realistic propagation models at the mm-wave band.

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