UTD-PO Formulation for the Analysis of Multiple-Plateau Diffraction when considering Illumination from a Low Source

José-Víctor Rodríguez, María-Teresa Martínez Inglés, José-María Molina-García-Pardo, Leandro Juan-Llácer, *Senior Member, IEEE*, Takeo Fujii, and Ignacio Rodríguez-Rodríguez

What is the problem being addressed by the manuscript and why is it important to the Antennas & Propagation community? (limited to 100 words).

The analysis of radiowave multiple-diffraction over a series of obstacles is essential for the planning of mobile communication systems in urban areas. Many formulations have been proposed in this sense. Such solutions usually model the obstacles as knife-edges and assume an angle of incidence greater than zero over the obstacles. However, in microcellular systems, the transmitter can be located below the average rooftop level, and obstacles should be modeled as rectangular sections to obtain more realistic results. A UTD-PO formulation for multiple-plateau diffraction when considering illumination from a low spherical source, which overcomes the limitations of previous methods, is presented.

What is the novelty of your work over the existing work? (limited to 100 words).

The proposed UTD-PO solution overcomes the limitations of previous methods especially when the distance between the transmitter and receiver increases (a greater number of blocks is considered). This way, the agreement of the presented UTD-PO formulation with measurements is excellent, contrary to what is observed with other existing methods. Moreover, the main advantage of the proposed solution is that, due to recursion, the calculations imply only single diffractions, thereby avoiding the need of higher-order diffraction terms in the diffraction coefficients.

Provide up to three references, published or under review, (journal papers, conference papers, technical reports, etc.) done by the authors/coauthors that are closest to the present work. Upload them as supporting documents if they are under review or not available in the public domain. Enter “N.A.” if it is not applicable.

- J-V. Rodríguez, J-M. Molina-Garcia-Pardo, and L. Juan-Llácer, “A new solution expressed in terms of UTD coefficients for the multiple diffraction of spherical waves by a series of buildings”, *Radio Sci.*, vol. 42, RS4011, 2007, DOI: 10.1029/2006RS003464.

- M. Martinez-Ingles, J. Pascual-García, J.-V. Rodríguez, R. López-Moya, J.-M. Molina-Garcia-Pardo and L. Juan-Llácer, "UTD-PO Solution for Estimating the Propagation Loss due to the Diffraction at the Top of a Rectangular Obstacle When Illuminated from a Low Source," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 12, pp. 6247-6250, Dec. 2013. doi: 10.1109/TAP.2013.2281822.

Provide up to three references (journal papers, conference papers, technical reports, etc.) done by other authors that are most important to the present work. Enter “N.A.” if it is not applicable.

- S. Tang and G. Lu, "Using parabolic equation to predicate the propagation-loss of the rooftops of buildings in urban environments," *2nd IEEE International Conference on Computer and Communications (ICCC)*, Chengdu, 2016, pp. 1479-1482. doi: 10.1109/CompComm.2016.7924948.

- E. Torabi, A. Ghorbani and A. Tajvidy, "A Modified Diffraction Coefficient for Imperfect Conducting Wedges and Buildings with Finite Dimensions," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 1197-1207, April 2009. doi: 10.1109/TAP.2009.2015795.

UTD-PO Formulation for the Analysis of Multiple-Plateau Diffraction when considering Illumination from a Low Source

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***Abstract*— A hybrid uniform theory of diffraction-physical optics (UTD-PO) formulation for the analysis of the multiple-diffraction (MD) that takes place over rectangular-shaped obstacles (plateaus) when the latter are illuminated from a low source is presented. The solution, which is based on Babinet's principle, has been validated with measurements taken at 60 GHz on a scaled model of the environment under study as well as with additional measurements performed by other authors. Moreover, the proposed approach has been compared with the wide-angle Fourier split-step parabolic equation method, with the UTD-PO formulation showing better accuracy against experimental data, especially when the distance between the transmitter and the receiver is increased. Furthermore, the main advantage of the proposed solution is that, due to recursion, the calculations imply only single diffractions, thereby avoiding the need of higher-order diffraction terms in the diffraction coefficients.**

The results and findings of this work are particularly applicable to the planning of microcellular mobile communication systems when the transmitting antenna is located below the height of the surrounding buildings.

***Index Terms*— Mobile communication, multiple diffraction, rectangular obstacles, UTD, PO.**

I. Introduction

THE analysis of the multiple-diffraction (MD) phenomenon which arises when an incident electromagnetic wave impinges over a series of obstacles can be essential in several contexts, such as the planning of mobile communication systems in urban areas [1,2]. Hence, a large number of formulations has been proposed in order to predict the radio signal attenuation caused by this phenomenon along the rooftops of buildings. Such solutions usually model the obstacles as knife-edges of equal height and assume either a plane-wave incidence [3-5] or a spherical-wave incidence [6,7]. Nevertheless, if a more complex and realistic approach is desired, buildings should be modeled as wedges [8] or, more realistically, as rectangular sections, as considered in formulations presented in works such as [9,10,11] (for plane-wave incidence), and [7,12] (for spherical-wave incidence). In these solutions, the angle of incidence over the obstacles is assumed to be greater than zero (that is, the transmitter height is greater than the average building height).

However, in microcellular mobile communication systems (where it would be better to consider a spherical-wave incidence assumption [13]), the transmitting source can be located below the average rooftop level, leading to a negative angle of incidence over the array of rectangular-shaped obstacles (plateaus). This situation has been studied −regarding MD phenomena− in different works [14-16]; all, however, consider only one block (building). Therefore, a more in-depth analysis is required of the MD caused by a series of plateaus of equal height when illuminated from a low spherical source. A solution based on the wide-angle Fourier split-step parabolic equation method (FSSPEM) was recently presented for this purpose [17]. However, its agreement with measurements begins to fail when the distance between transmitter and receiving point is progressively increased (that is, when a greater number of buildings is considered).

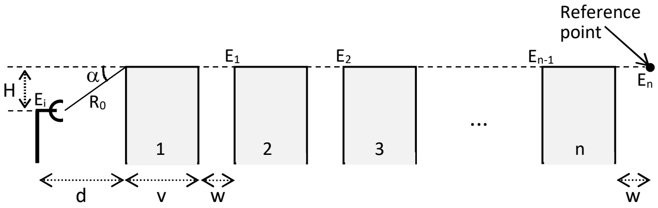

Fig. 1. Propagation scenario under consideration.

Regarding the above, in this work, a hybrid uniform theory of diffraction-physical optics (UTD-PO) formulation which overcomes the limitations of previous methods, is presented for the analysis of multiple-plateau diffraction when considering illumination from a low spherical-wave source (negative angle of incidence). The proposed solution combines the UTD-PO recursive approach based on virtual spherical sources presented by some of the authors in [7] with the fact that the diffraction over one block from a low source can be broken down –through Babinet's principle− into just single and double knife-edge diffractions (as shown by the authors in [16]). This way, the limitation of the UTD-PO approach in [7] for the case of rectangular plateaus with illumination from below is overcome. Such limitation consisted of the impossibility to analyze negative angles of incidence due the fact that, since the rectangular obstacles are seen as a series of wedges made of interior angle $\pi/2$ radians −joined two by two−, the spherical waves would hit the right-placed wedges forming the block cross-sections from inside the obstacle, which is meaningless. Moreover, the main advantage of the proposed solution is that, due to recursion, the calculations imply only single diffractions, thereby avoiding the need of higher-order diffraction terms in the diffraction coefficients while at the same time achieving good accuracy. The solution is validated with measurements performed at 60 GHz on a scaled model of the environment under consideration (which, as shown in [18][19], can be an appropriate method to obtain reliable and useful results to be employed in real-world scenarios). Moreover, the formulation is also compared with the FSSPE method proposed in [17]. The results and findings of this work are particularly applicable to the planning of microcellular mobile communication systems when the transmitting antenna is located below the height of the surrounding buildings.

II. Propagation Environment

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In Fig. 1, a scheme of the scenario under consideration in this work shows a series of n perfectly conducting rectangular obstacles of equal height, width v, and constant inter-spacing w. The reference point (receiver) is assumed to be located at the same level as the top of the blocks (where, if an array of buildings is under study, an eventual final diffraction down to a receiver positioned at street level would take place), and at a distance w from the last obstacle. The transmitting source, on the other hand, is located at a distance d from the first block (spherical-wave incidence) and below the blocks height, at a downward distance H from the top of the rectangular obstacles, so that the incident wave impinges over the first block with a negative angle α.

III. Theoretical Formulation

If we first consider the case of n=1 (see Fig. 2), following the formulation published by some of the authors in [16] for the analysis of diffraction over one rectangular obstacle when illuminated from below –where Babinet's principle is applied–, the field E_1 (which can also be named as E_{10} in accordance with the formulation for n>1 which will be explained next) can be obtained as:

$$E_1 = E_{10} = E'_{10} \pm E''_{10} - E'''_{10} \quad (1).$$

That is, the summation of one component which accounts for propagation over a double knife-edge instead of the rectangular obstacle (E'_{10}) and another which considers the reflection caused on the top of the block (E''_{10}–E'''_{10}, i. e. the difference between a single diffraction over the second knife-edge in the absence of the first –with an angle of incidence α_1 and illumination from above– and a double knife-edge diffraction –with an angle of incidence α and, again, illumination from above–), where '+' is considered for *hard* polarization and '–' for *soft* polarization, with

$$\begin{aligned} E'_{10} = \frac{1}{2}\Bigg[& \frac{E_i}{R_0} e^{-jkR_0} \sqrt{\frac{R_0}{(v+w)(R_0+v+w)}} \\ & D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha, L = \frac{R_0(v+w)}{R_0+(v+w)}\right) e^{-jk(v+w)} \\ & + E(1)\sqrt{\frac{R_0}{w(R_0+w)}} D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha, L = \frac{R_0 w}{R_0+w}\right) e^{-jkw} \Bigg] \end{aligned} \quad (2)$$

where: Ei is the relative amplitude of the spherical source (which has been assumed in this case as 1), k is the wavenumber, $D(\phi, \phi', L)$ is the UTD diffraction coefficient for a knife-edge presented in [20], and

$$R_0 = \sqrt{H^2 + d^2} \quad (3)$$

$$\alpha = atan\left(\frac{H}{d}\right) \quad (4)$$

$$E(1) = \frac{E_i}{R_0} e^{-jkR_0} \sqrt{\frac{R_0}{v(R_0+v)}} D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha, L = \frac{R_0 v}{R_0+v}\right) e^{-jkv} \quad (5)$$

$$\begin{aligned} E''_{10} = & \frac{E_i}{R_2} e^{-jkR_2} + \frac{E_i}{R_1} e^{-jkR_1} \sqrt{\frac{R_1}{w(R_1+w)}} \\ & D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha_1, L = \frac{R_1 w}{R_1+w}\right) e^{-jkw} \end{aligned} \quad (6)$$

$$R_1 = \sqrt{H^2 + (d+v)^2} \quad (7)$$

$$R_2 = \sqrt{H^2 + (d+v+w)^2} \quad (8)$$

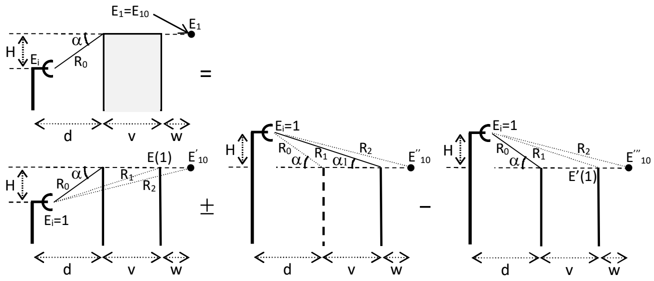

Fig. 2. Geometry for n=1.

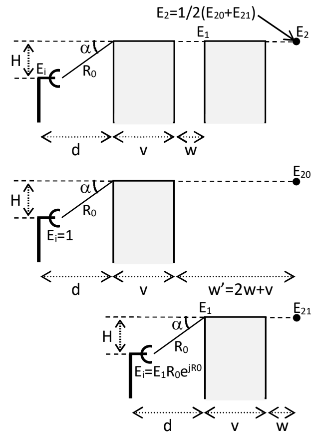

Fig. 3. Geometry for n=2.

$$\alpha_1 = atan\left[\frac{H}{(d+v)}\right] \quad (9)$$

$$\begin{aligned} E'''_{10} = \frac{1}{2}\Bigg[& \frac{E_i}{R_0} e^{-jkR_0} \Bigg(\frac{R_0}{R_2} e^{-jk(R_2-R_0)} + \sqrt{\frac{R_0}{(v+w)(R_0+v+w)}} \\ & D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha, L = \frac{R_0(v+w)}{R_0+(v+w)}\right) e^{-jk(v+w)} \Bigg) \\ & + E'(1) \Bigg[\frac{R_0}{R'_1} e^{-jk(R_2-R_1)} + \sqrt{\frac{R_0}{w(R_0+w)}} \\ & D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha, L = \frac{R_0 w}{R_0+w}\right) e^{-jkw} \Bigg] \Bigg] \end{aligned} \quad (10)$$

$$\begin{aligned} E'(1) = & \frac{E_i}{R_0} e^{-jkR_0} \Bigg[\frac{R_0}{R_1} e^{-jk(R_1-R_0)} \\ & + \sqrt{\frac{R_0}{v(R_0+v)}} D\left(\phi = \frac{3\pi}{2}, \phi' = \frac{\pi}{2} + \alpha, L = \frac{R_0 v}{R_0+v}\right) e^{-jk} \Bigg] \end{aligned} \quad (11)$$

$$R'_1 = \sqrt{H^2 + (d+w)^2} \quad (12)$$

Then, for n=2 (see Fig. 3), by considering the UTD-PO recursive approach based on virtual spherical sources presented by some of the authors in [7], the field E_2 can be calculated as the average of the contributions (E_{20} and E_{21}) which result from the consideration of the spherical wave fronts indicated in Fig. 3 impinging over each obstacle separately (with E_i=1 for E_{20} and $E_i=E_1R_oe^{jRo}$ for E_{21}, being that E_1 has been calculated in the previous iteration). This way,

$$E_2 = \frac{1}{2}(E_{20} + E_{21}) \quad (13)$$

with E_{20} and E_{21} calculated in the same way as for E_{10}, except from the facts that, for E_{20}, w is now $w'=2w+v$ and, for E_{21}, as already mentioned, $E_i=E_1R_oe^{jRo}$ instead of 1.

Therefore, regarding the above, if we generalize the previous process for the case of n plateaus (by considering both the mentioned UTD-PO recursive approach based on virtual spherical sources and the fact that, as previously stated, the diffraction over one block from a low source can be broken down –through Babinet's principle– into just single and double knife-edge diffractions), the total field E_n reaching the reference point indicated in Fig. 1 can be obtained as follows (see Fig. 4):

$$E_n = \frac{1}{n}\sum_{m=0}^{n-1} E_{nm} \quad (14)$$

where:

$$E_{nm} = E'_{nm} \pm (E''_{nm} - E'''_{nm}) \quad (15)$$

with

$$E'_{nm} = \frac{1}{2}\left[\frac{E_i}{R_0}e^{-jkR_0}\sqrt{\frac{R_0}{(v+w')(R_0+v+w')}}\right.$$
$$D\left(\phi=\frac{3\pi}{2},\phi'=\frac{\pi}{2}+\alpha,L=\frac{R_0(v+w')}{R_0+(v+w')}\right)e^{-jk(v+w')} \quad (16)$$
$$\left.+E(1)\sqrt{\frac{R_0}{w'(R_0+w')}}D\left(\phi=\frac{3\pi}{2},\phi'=\frac{\pi}{2}+\alpha,L=\frac{R_0w'}{R_0+w'}\right)e^{-jkw'}\right]$$

where R_0, α and $E(1)$ should be considered as in (3), (4), and (5), respectively, and

$$E_i = \begin{cases} 1 & if\ m=0 \\ E_mR_0e^{jk\ _0} & if\ m\neq 0 \end{cases} \quad (17)$$

$$w' = (n-m)w + (n-m-1)v \quad (18)$$

$$E''_{nm} = \frac{E_i}{R_2}e^{-jkR_2} + \frac{E_i}{R_1}e^{-jkR_1}\sqrt{\frac{R_1}{w'(R_1+w')}}$$
$$D\left(\phi=\frac{3\pi}{2},\phi'=\frac{\pi}{2}+\alpha_1,L=\frac{R_1w'}{R_1+w'}\right)e^{-jkw'} \quad (19)$$

with E_i as in (17), and R_1 and α_1 as in (7) and (9), respectively, and

$$R_2 = \sqrt{H^2+(d+v+w')^2} \quad (20)$$

and, finally,

$$E'''_{nm} = \frac{1}{2}\left[\frac{E_i}{R_0}e^{-jkR_0}\left(\frac{R_0}{R_2}e^{-j\ (R_2-R_0)}+\sqrt{\frac{R_0}{(v+w')(R_0+v+w')}}\right.\right.$$
$$\left.D\left(\phi=\frac{3\pi}{2},\phi'=\frac{\pi}{2}+\alpha,L=\frac{R_0(v+w')}{R_0+(v+w')}\right)e^{-jk(v+w')}\right) \quad (21)$$
$$+E'(1)\left[\frac{R_0}{R'_1}e^{-jk(R_2-R_1)}+\sqrt{\frac{R_0}{w'(R_0+w')}}\right.$$
$$\left.\left.D\left(\phi=\frac{3\pi}{2},\phi'=\frac{\pi}{2}+\alpha,L=\frac{R_0w'}{R_0+w'}\right)e^{-jkw'}\right]\right]$$

with $E'(1)$ as in (11), E_i as in (17), and

$$R'_1 = \sqrt{H^2+(d+w')^2} \quad (22)$$

IV. Measurement Setup

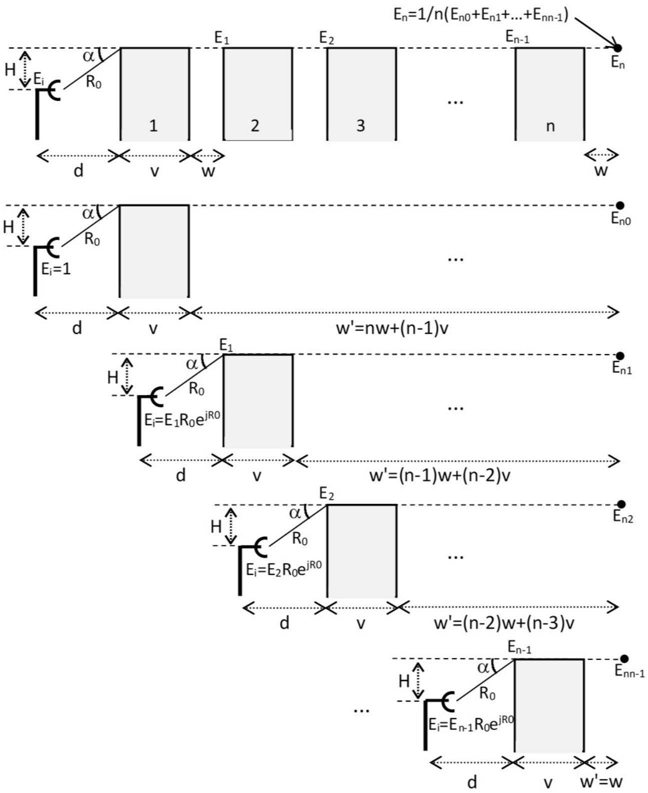

Fig. 4. Geometry for n plateaus.

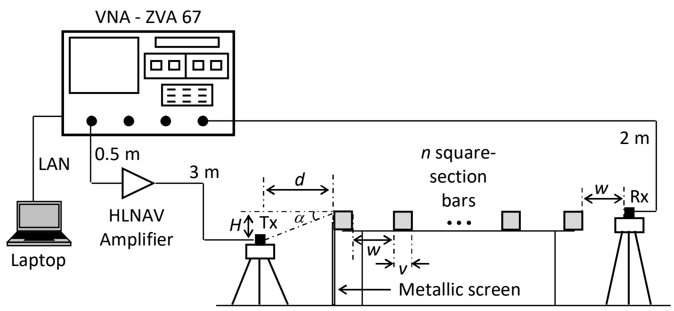

Fig. 5. Scheme of the measurement setup.

The scheme of the measurement setup considered in this work can be seen in Fig. 5. It should be noted that this setup is the same as that employed in [21][22] (where a solution for MD analysis considering positive angles of incidence over an array of dielectric plateaus was validated with measurements). However, in our case, a series of n perfectly-conducting (metallic) square-section bars of width v=0.04 m was taken into consideration, along with a negative incident angle α. Moreover, the insertion losses of the coaxial cable are 6 dB/m at 60 GHz and the gain of the antennae range from 4.3 to 4.8 dBi within the frequency band taken into account: 58 to 62 GHz. Furthermore, the 3dB elevation beam width varies from 33° to 24°, while being omni-directional in the horizontal plane. The ZVA67 Rohde & Schwarz vector network analyzer (VNA) employed in the measurements bears a dynamic range −for the 50 to 65 GHz band− of >107 dB (typ. 115 dB), and its measurement accuracy can be found in [23]. Moreover, it should be noted that the measurement setup could be subject to different errors which might come from the variation of the VNA's resolution, misalignments of the antennas, etc.

Measurements were performed for three different values of n (1, 3, 5), w=0.192 m, *soft* polarization, and two values of d (0.10 and 0.20 m). The transmitting antenna height H was varied from -0.02 m to 0 m in steps of 0.0025 m, when d=0.20 m, and from -0.01 to 0 m with the same steps, when d=0.10 m. Moreover, as shown in Fig. 5, a metallic screen was positioned at the first bar in order to remove any contribution coming from below the series of obstacles.

The channel frequency response was undertaken at 301 frequency points, equally spaced between 58 GHz and 62 GHz, leading to a frequency step of 13.3 MHz, with 1 Hz being the intermediate frequency. As we selected 301 measurement points, we were able to measure a maximum distance of 301/BW*3e8 = 22.6 m without time aliasing (the maximum dimension of the measurement environment was 7 m). The power transmitted by the VNA was -10 dBm, giving a dynamic range of more than 100 dB at 60 GHz, and the *time-gating technique* described in [21] was properly applied. This technique permits us to select MD contributions while simultaneously removing the remaining undesirable contributions.

V. Results

Fig. 6 shows the total attenuation (MD losses and free-space loss) at the reference point shown in Fig. 1, obtained using the proposed UTD-PO formulation. Parameters of frequency=9.375 GHz, v=0.1 m, w=0.4 m, d=0.162 m, H=-0.03 m (α=-10.5°), and *hard* polarization were considered. For comparison purposes, the results obtained for this scenario by using the FSSPE method proposed in [17] are also shown in the plot, along with the measurements performed in the cited work. As can be observed, a solid agreement is found between the outcomes of the UTD-PO solution and the measurements. However, when compared with the empirical data, the FSSPE formulation shows a certain inaccuracy, which becomes greater as the number of plateaus increases (that is, as the distance between the transmitter and receiver grows). Moreover, as an extra validation of the proposed UTD-PO formulation, a comparison between the knife-edge case (with a 0.5 m spacing) −calculated with the method presented in [7]− and the UTD-PO solution of the present work when considering v=0 m and w=0.5 m is also shown in the plot. As can be seen, an excellent agreement is found between both curves.

In Figs. 7 and 8, the attenuation relative to the free-space field (MD losses) obtained at the receiver (Rx) shown in Fig. 5 through the proposed UTD-PO formulation is shown −for d=0.10 m and d=0.20 m, respectively− and compared with the measurements on the scaled model performed by the authors, at 60 GHz, and explained in the previous section. As can be observed, an excellent agreement is found between the measurements and the UTD-PO solution proposed in the current study, with a maximum difference of 0.48 dB for d=0.10 m (when H=-0.005 m and n=5) and 0.52 dB for d=0.20 m (when H=-0.0025 m and n=3). In any case, in order to quantify such agreement, in Table I, the mean and the variance of the error (in dB) between the theoretical results and the measured values are shown. As can be observed, the statistical parameters exhibit a small error between both outcomes for all the cases considered.

V. Conclusions

A UTD-PO solution, based on Babinet's principle, to calculate MD attenuation of radio waves caused by rectangular-shaped obstacles (plateaus) when illuminated from a low source has been presented. The formulation has been successfully validated through solid agreement with measurements (both those taken by the authors and those published in other works). Moreover, the UTD-PO model has been compared with the wide-angle FSSPE method, with the results

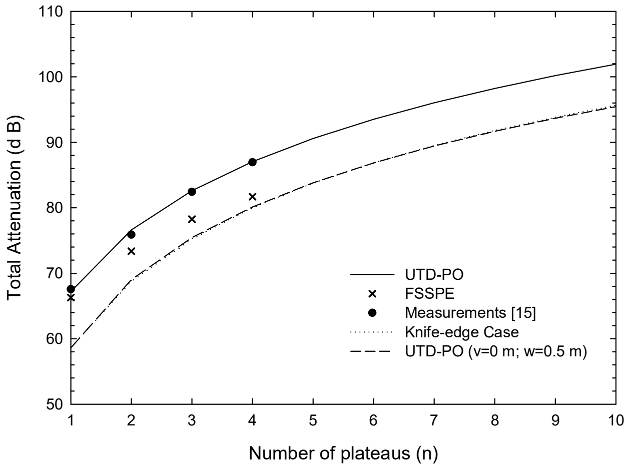

Fig. 6. Comparison of the total attenuation (MD losses and free-space loss) at the reference point shown in Fig. 1, as a function of n, between the UTD-PO solution and the FSSPE method/measurements presented in [15]. Frequency=9.375 GHz, v=0.1 m, w=0.4 m, d=0.162 m, H=-0.03 m, and *hard* polarization. A comparison between the knife-edge case and the proposed UTD-PO solution with v= 0 m and w=0.5 m is also shown in the plot.

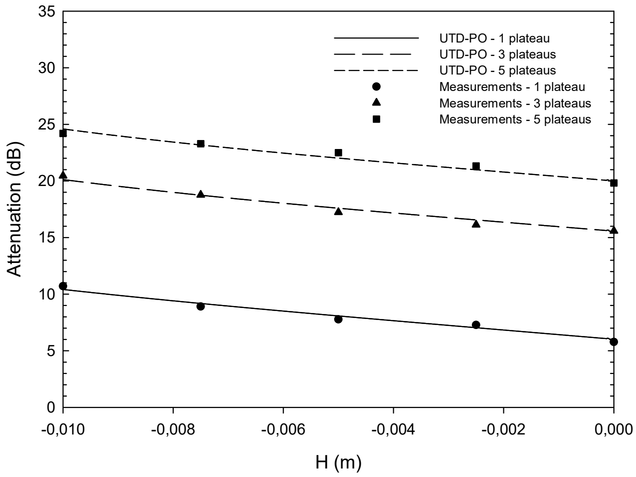

Fig. 7. Comparison of the attenuation obtained with the UTD-PO solution, as a function of H, and measurements. Frequency=60 GHz, n=1-3-5, d=0.10 m, w=0.192 m, v=0.04 m, and *soft* polarization.

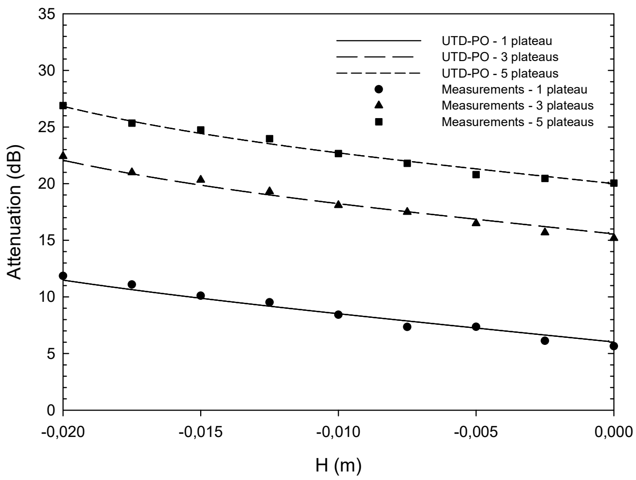

Fig. 8. Comparison of the attenuation obtained with the UTD-PO solution, as a function of H, and measurements. Frequency=60 GHz, n=1-3-5, d=0.20 m, w=0.192 m, v=0.04 m, and *soft* polarization.

showing how the former achieves better accuracy than the latter when both formulations are contrasted with experimental data, especially when the distance between the transmitter and the receiver is increased (that is, a greater number of blocks is considered).

The results and findings of this work are especially applicable to the planning of microcellular mobile communication systems when the transmitting antenna is located below the height of the surrounding buildings.

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TABLE I
MEAN AND VARIANCE OF THE ERROR BETWEEN THE THEORETICAL RESULTS AND THE MEASUREMENTS (dB).

	Mean Error	**Variance**
***n*=1 (*d*=0.10 m)**	0.276	0.001
***n*=1 (*d*=0.20 m)**	0.327	0.027
***n*=3 (*d*=0.10 m)**	0.241	0.039
***n*=3 (*d*=0.20 m)**	0.289	0.027
***n*=5 (*d*=0.10 m)**	0.297	0.021
***n*=5 (*d*=0.20 m)**	0.217	0.028

REFERENCES

[1] O. Ozgun, "Modeling of diffraction effects in urban radiowave propagation". *Applied Computational Electromagnetics Society Journal*, vol. 32, pp. 593-599, 2017.

[2] S. P. Sotiroudis and K. Siakavara, "Mobile radio propagation path loss prediction using Artificial Neural Networks with optimal input information for urban environments." *AEU - International Journal of Electronics and Communications*, vol. 69(10), pp. 1453–1463, 2015. doi:10.1016/j.aeue.2015.06.014.

[3] J. Walfisch and H. L. Bertoni, "A theoretical model of UHF propagation in urban environments", *IEEE Trans. Ant. and Prop.*, vol. 36, no. 12, pp. 1788-1796, Dec. 1988. doi: 10.1109/8.14401.

[4] S. R. Saunders and F. R. Bonar, "Explicit Multiple Building Diffraction Attenuation Function for Mobile Radio Wave Propagation", *Electron. Lett.*, vol. 27, no. 14, pp. 1276-1277, Jul. 1991.

[5] L. Juan-Llácer and N. Cardona, "UTD Solution for the multiple building diffraction attenuation function for mobile radiowave propagation", *Electron. Lett.*, vol. 33, no. 1, pp. 92-93, Jan. 1997.

[6] H. H. Xia and H. L. Bertoni, "Diffraction of Cylindrical and Plane Waves by an Array of Absorbing Half-Screens", *IEEE Trans. on Ant. and Prop.*, vol. 40, no. 2, pp. 170-177, Feb. 1992.

[7] J-V. Rodríguez, J-M. Molina-Garcia-Pardo, and L. Juan-Llácer, "A new solution expressed in terms of UTD coefficients for the multiple diffraction of spherical waves by a series of buildings", *Radio Sci.*, vol. 42, RS4011, 2007, DOI: 10.1029/2006RS003464.

[8] V. Daniele, G. Lombardi and R. S. Zich, "The Double PEC Wedge Problem: Diffraction and Total Far Field," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 6482-6499, Dec. 2018, doi: 10.1109/TAP.2018.2877260.

[9] Tajvidy, A., Pourmina, M.A., Naser-Moghadasi, M. et al. "An Improved UTD Based Model for the Multiple Building Diffraction of Plane Waves in Urban Environments by Using Higher Order Diffraction Coefficients". *Wireless Pers Commun* 72, 2577–2586, 2013 doi:10.1007/s11277-013-1167-z.

[10] J.-V. Rodríguez, J.M. Molina-Garcia-Pardo and L. Juan-Llacer, "An improved solution expressed in terms of UTD coefficients for the multiple-building diffraction of plane waves", *IEEE Antennas and Wireless Propagation Letters*, vol. 4, pp. 16-19, 2005. doi: 10.1109/LAWP.2004.841624.

[11] J. -V. Rodríguez, T. Fujii, L. Juan-Llácer, J. -M. Molina-García-Pardo and I. Rodríguez-Rodríguez, "Plane-Wave UTD-PO Formulations for Multiple-Diffraction by Trees and Buildings at Millimeter-Wave Frequencies," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 10, pp. 1793-1797, Oct. 2020, doi: 10.1109/LAWP.2020.3018561.

[12] E. Torabi, A. Ghorbani and A. Tajvidy, "A Modified Diffraction Coefficient for Imperfect Conducting Wedges and Buildings with Finite Dimensions," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 4, pp. 1197-1207, April 2009. doi: 10.1109/TAP.2009.2015795.

[13] J.-V. Rodríguez, J.-M. Molina-Garcia-Pardo and L. Juan-Llacer, "Comparison of spherical against plane-wave incidence assumption in prediction of over-rooftop multiple-building diffraction," *IET Microwaves, Antennas & Propagation*, vol. 1, no. 3, pp. 729-732, June 2007. doi: 10.1049/iet-map:20060178

[14] J. H. Whitteker, "Diffraction over a flat-topped terrain obstacle", *IEE Proc. H.*, vol. 137, no. 2, pp. 113–116, 1990.

[15] C. J. Haslett and M. O. Al-Nuaimi, "Prediction of diffracted field strength in the shadow of a flat roofed building", *Electron. Lett.*, vol. 27, no. 11, pp. 950–951, 1991.

[16] M. Martinez-Ingles, J. Pascual-García, J.-V. Rodríguez, R. López-Moya, J.-M. Molina-Garcia-Pardo and L. Juan-Llácer, "UTD-PO Solution for Estimating the Propagation Loss due to the Diffraction at the Top of a Rectangular Obstacle When Illuminated from a Low Source," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 12, pp. 6247-6250, Dec. 2013. doi: 10.1109/TAP.2013.2281822.

[17] S. Tang and G. Lu, "Using parabolic equation to predicate the propagation-loss of the rooftops of buildings in urban environments," *2nd IEEE International Conference on Computer and Communications (ICCC)*, Chengdu, 2016, pp. 1479-1482. doi: 10.1109/CompComm.2016.7924948.

[18] D. Erricolo and L. E. Uslenghi, "Two-dimensional simulator for propagation in urban environments," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 4, pp. 1158-1168, July 2001, doi: 10.1109/25.938590.

[19] D. Erricolo, G. D'Elia, and P. L. E. Uslenghi, "Measurements on scaled models of urban environments and comparisons with ray-tracing propagation simulation," *IEEE Trans. Antennas Propag.*, vol. 50, no. 5, pp. 727–735, 2002.

[20] R. G. Kouyoumjian and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface", *Proc. IEEE*, vol. 62, no. 11, pp. 1448-1461, Nov. 1974.

[21] M.-T. Martínez-Inglés, J-V. Rodríguez, J-M. Molina-Garcia-Pardo, J. Pascual-García, and L. Juan-Llácer, "Comparison of a UTD-PO Formulation for Multiple-Plateau Diffraction with Measurements at 62 GHz", *IEEE Trans. on Antennas and Propagation*, vol. 61, no. 2, pp. 1000–1003, Feb. 2013.

[22] M.-T. Martínez-Inglés, "Theoretical and experimental characterization of the 60 GHz radiocommunication channel", *Ph.D dissertation*, Universidad Politécnica de Cartagena, Spain and Lille University, France, 2014.

[23] https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_common_library/dl_brochures_and_datasheets/pdf_1/ZVA_dat-sw_en_5213-5680-22_v1100.pdf.