Novel Heuristic UTD Coefficients for the Characterization of Radio Channels

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This paper presents novel heuristic coefficients for the uniform theory of diffraction (UTD), suited to analyze the scattering by lossy conducting wedges in an efficient and reciprocal manner. For its reciprocal properties, the coefficients are appropriate to handle complex scenarios with arbitrary transmitter and receiver positions. The new coefficients take advantage of two previously proposed heuristic coefficients, combining both in a novel approach. The diffraction by arbitrary conducting wedges is investigated and results are compared with those given by accurate Maliuzhinets and method-of-moments analyses. The proposed technique is then applied to characterize the scattering through a typical urban scenario in order to demonstrate its applicability.

***Index Terms*—Heuristic diffraction coefficients, scattering by lossy wedges, uniform theory of diffraction (UTD).**

I. Introduction

SEVERAL techniques have been developed to analyze the propagation of electromagnetic waves through complex environments. Among them, the uniform theory of diffraction (UTD) has been playing an important role, for its versatility and computational efficiency. The UTD coefficients were developed by Kouyoumjian and Pathak for perfectly conducting wedges [1].

The estimation of the diffracted field by lossy conducting wedges is not a simple task [2]–[6]. Diffraction coefficients were heuristically proposed by Luebbers to take into account ground losses in the analysis of obstructed VHF and UHF radio links [2]. These heuristic coefficients present some problems, especially in deep shadow regions and when the diffracted ray leaves the wedge close to one of its walls. Luebbers' coefficients also present difficulties associated with reciprocity, as they were derived for forward scattering analysis [2]. Luebers' coefficients gained much attention, motivating developments to minimize their drawbacks [3], [4]. In [3], Aïdi and Lavergnat heuristically proposed new definitions for the angle of incidence, turning Luebbers' coefficients into reciprocal ones. Independently, Holm applied the Fresnel–Kirchhoff theory to derive novel heuristic coefficients with superior performance deep in the shadow region [4]. However, likewise Luebbers', Holm's coefficients do not obey reciprocity.

Thus, our aim is to apply the angular definitions of [3] into Holm's heuristic coefficients [4], in order to heuristically establish efficient and reciprocal diffraction coefficients suited for lossy wedge scattering and, consequently, radio channel characterizations. In order to estimate the usefulness and applicability of the proposed coefficients, scattering by arbitrary lossy wedges are investigated. The results obtained by the proposed UTD heuristic coefficients are compared against those obtained via Maliuzhinets' coefficients [6], the method of moments (MoM) [7], and pathloss measurements in a typical urban scenario [8].

II. Heuristic UTD Coefficients for Lossy Wedges

A. Luebbers' Heuristic Diffraction Coefficients

In [2], Luebbers' soft and hard heuristic diffraction coefficients are described as

$$D^{s,h}=G_0^{s,h}\left[D_2+R_0^{s,h}(\alpha_0)D_4\right]+G_n^{s,h}\left[D_1+R_n^{s,h}(\alpha_n)D_3\right] \tag{1}$$

where D_i, for $i=1,\dots,4$, are the UTD diffraction coefficients, as defined in [1], and R_0 and R_n are the Fresnel reflection coefficients, relative to 0 ($\phi=0$) and n ($\phi=n\pi$) wedge faces, respectively (see Fig. 1). The superscripts s and h denote the soft and hard polarizations, respectively, for which the Fresnel reflection coefficients are

$$R^s(\alpha)=\frac{\sin(\alpha)-\sqrt{\hat{\varepsilon}_{\rm r}-\cos^2(\alpha)}}{\sin(\alpha)+\sqrt{\hat{\varepsilon}_{\rm r}-\cos^2(\alpha)}},$$
$$R^h(\alpha)=\frac{\hat{\varepsilon}_{\rm r}\sin(\alpha)-\sqrt{\hat{\varepsilon}_{\rm r}-\cos^2(\alpha)}}{\hat{\varepsilon}_{\rm r}\sin(\alpha)+\sqrt{\hat{\varepsilon}_{\rm r}-\cos^2(\alpha)}} \tag{2}$$

where $\hat{\varepsilon}_{\rm r}=\varepsilon_{\rm r}-j\sigma/(\omega\varepsilon_0)$ is the wedge complex relative permittivity and the incidence angles α_0 and α_n are

$$\alpha_0=\min(\phi_i,\phi_d),\quad \alpha_n=\min(n\pi-\phi_i,n\pi-\phi_d) \tag{3}$$

where $n\pi$ is the wedge exterior angle, ϕ_i is the direction of the incident wave, and ϕ_d is the direction of the diffracted wave, both with respect to face 0 (see Fig. 1). The factors $G_0^{s,h}$ and $G_n^{s,h}$, used when grazing incidence occurs, are

$$G_n^{s,h}=\begin{cases}1/2, & \phi_i=0\\ 1/\left(1+R_n^{s,h}\right), & \phi_{\rm i}=n\pi,\left(1+R_n^{s,h}\right)>0\\ 1, & \text{otherwise}\end{cases} \tag{4}$$

$$G_0^{s,h}=\begin{cases}1/2, & \phi_i=n\pi\\ 1/\left(1+R_0^{s,h}\right), & \phi_{\rm i}=0,\left(1+R_0^{s,h}\right)>0\\ 1, & \text{otherwise}\end{cases} \tag{5}$$

Digital Object Identifier 10.1109/TMAG.2006.890975

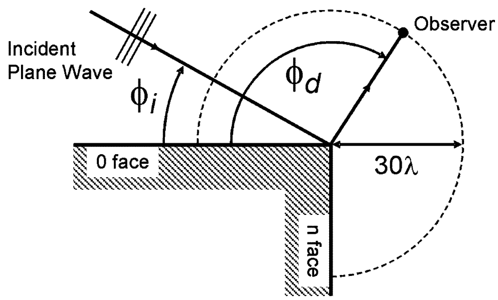

Fig. 1. Right-angle lossy wedge with $\varepsilon_r = 10$ and $\sigma = 0.01$ S/m.

B. Aïdi and Lavergnat Heuristic Diffraction Coefficients

In [3], new definitions were proposed for α_0 and α_n, in order to make Luebbers' heuristic coefficients reciprocal

$$\alpha_0 = \alpha_n = \min(\phi_i, \phi_d, n\pi - \phi_i, n\pi - \phi_d) \tag{6}$$

instead of (3). With this simple modification, the diffraction coefficients are reciprocal, i.e., they are (heuristically) valid independent of the transmitter and receiver positions with respect to wedge faces 0 and n [3]. Case studies indicate that superior performance is achieved, especially in the regions close to the wedge faces [3].

C. Holm's Heuristic Diffraction Coefficients

In [4], a modification in the term D_1 of (1) was proposed in order to account for wedges with interior angles greater than π (i.e., interior wedges) and obtain better performance than Luebbers' coefficients in deep shadow regions. Holm's heuristic coefficients are [4]

$$D^{s,h} = G_n^{s,h}\left[R_0^{s,h}(\alpha_0)R_n^{s,h}(\alpha_n)D_1 + R_0^{s,h}(\alpha_0)D_4\right] + G_0^{s,h}\left[D_2 + R_n^{s,h}(\alpha_n)D_3\right] \tag{7}$$

where α_0 and α_n are those of (3). (Note that in [3], the coefficients D_i are differently numbered with respect to the classical notation in [1], which is the one adopted here.) Holm also proposed a change in the definition of the G factors

$$\begin{cases} G_0^{s,h} = G_n^{s,h} = 1/2, & \phi_\mathrm{i} = 0 \text{ or } \phi_\mathrm{i} = n\pi \\ G_0^{s,h} = G_n^{s,h} = 1, & \text{otherwise} \end{cases} \tag{8}$$

instead of (4) and (5). Using the coefficients (7), better estimates were achieved for diffraction in directions close to the wedge faces. However, reciprocity was not a concern [4].

D. Novel Heuristic Diffraction Coefficients for Lossy Conducting Wedges

The novel heuristic coefficients were developed aiming their application to coverage predictions in urban scenarios. This means that obstacles with various configurations and finite conductivity surfaces, together with arbitrary transmitter and receiver positions, must be accounted for practical estimates.

The results in [4] indicate that Holm's coefficients provide superior results than Luebbers' ones [2]. However, they are not reciprocal. So, for the consideration of arbitrarily located transmitters (sources) and receivers (observers), we propose the extension of Aïdi and Lavergnat angular definitions [3] to Holm's heuristic formulation, in order to make it reciprocal.

This is accomplished by initially noticing that the Fresnel reflection coefficients R_0 and R_n multiplying the term D_1 in (7) are appropriate in the case where the source of the incident field is in the side of the Fresnel–Kirchhoff integration surface where face 0 is present, which happens when $\phi_\mathrm{i} < \mathrm{n}\pi/2$ [4]. If not (i.e., if $\phi_\mathrm{i} \geq \mathrm{n}\pi/2$), then reciprocity imposes R_0 and R_n multiplying the factor D_2 instead of D_1 in (7). Consequently, the novel heuristic UTD coefficients read as

$$D^{s,h} = G_n^{s,h}\left[W_n^{s,h}D_1 + R_n^{s,h}(\alpha_n)D_3\right] + G_0^{s,h}\left[W_0^{s,h}D_2 + R_0^{s,h}(\alpha_0)D_4\right] \tag{9}$$

where $G_0^{s,h}$ and $G_n^{s,h}$ are used when grazing incidence occurs and are defined as in (8). W_n and W_0 are defined as

$$W_n^{s,h} = \begin{cases} R_0^{s,h}(\alpha_0)R_n^{s,h}(\alpha_n), & \phi_\mathrm{i} < n\pi/2 \\ 1, & \phi_\mathrm{i} \geq n\pi/2 \end{cases}$$
$$W_0^{s,h} = \begin{cases} 1, & \phi_\mathrm{i} < n\pi/2 \\ R_0^{s,h}(\alpha_0)R_n^{s,h}(\alpha_n), & \phi_\mathrm{i} \geq n\pi/2 \end{cases} \tag{10}$$

and the Fresnel reflection coefficients $R_0^{s,h}$ and $R_n^{s,h}$ are calculated with α_0 and α_n given by the Aïdi and Lavergnat angular definition (6).

E. Slope Diffraction

In the case of double-diffracted rays in consecutive wedges, the use of the first-order diffraction coefficients of (9) will estimate a null field for an observer in the shadow region. To overcome this problem, a second-order term (known as *slope diffraction*) must be considered. The slope diffraction term must be added to the first-order components to yield the total field. The slope diffraction coefficients depend on spatial derivatives of the incident field and of the coefficients in (9). The slope diffraction coefficients are similar to those presented in [4], just observing the new angular definitions of (6).

III. CASE STUDIES

A. Comparisons Among Different Heuristic Coefficients

In order to demonstrate the usefulness of the proposed UTD heuristic formulation, the several heuristic coefficients (i.e., Luebbers [2], Aïdi and Lavergnat [3], Holm [4], and the novel coefficients proposed in Section II-D) are compared to each other in the analysis of a plane-wave scattering by a right-angle lossy wedge with geometrical parameters depicted in Fig. 1. Both TM (soft) and TE (hard) polarizations are considered and an accurate asymptotic diffractive analysis based on Maliuzhinets' coefficients [6] is adopted as reference for the comparative study.

For both TM and TE plane-wave polarizations, the directions of incidence $\phi_i = \pi/6$ and $3\pi/4$ are considered. The operation frequency is 1 GHz, and the observations are made at a distance of 30λ from the edge, with the observation direction ϕ_d varying from 0 to $3\pi/2$ (see Fig. 1). The lossy wedge has a relative permittivity $\varepsilon_\mathrm{r} = 10$ and a conductivity $\sigma = 0.01$ S/m. In order

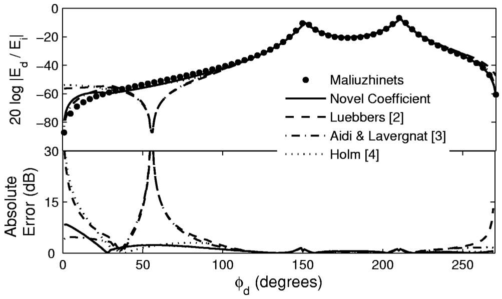

Fig. 2. TM diffracted field around the wedge of Fig. 1 ($\phi_i = \pi/6$).

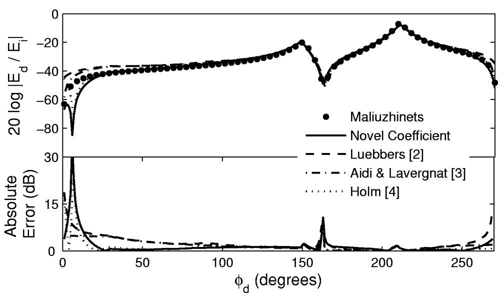

Fig. 3. TE diffracted field around the wedge of Fig. 1 ($\phi_i = \pi/6$).

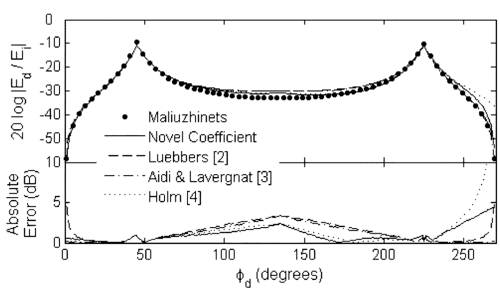

Fig. 4. TM diffracted field around the wedge of Fig. 1 ($\phi_i = 3\pi/4$).

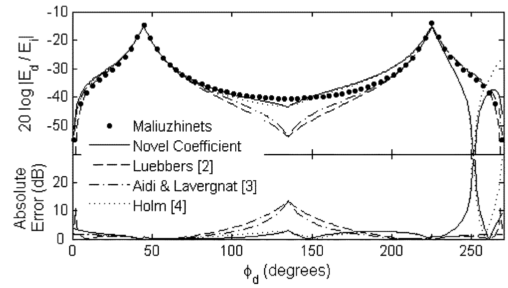

Fig. 5. TE diffracted field around the wedge of Fig. 1 ($\phi_i = 3\pi/4$).

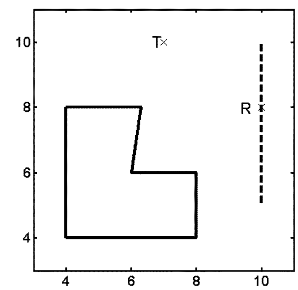

Fig. 6. Environment obstacles with $\varepsilon_r = 7$ and $\sigma = 0.2$ S/m.

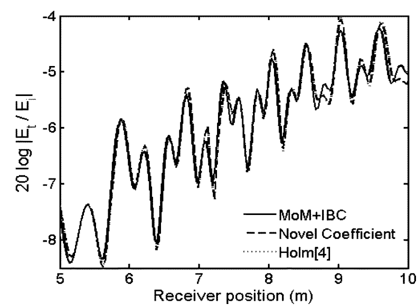

Fig. 7. TM electric field at the observation points depicted in Fig. 6.

to account for losses, the Maliuzhinets' coefficients make use of a surface impedance over the wedge faces, meaning that no energy is transmitted to the wedge interior [6].

Figs. 2–5 show the relative diffracted electric field amplitude $|E_d|$ (with respect to the incident electric field amplitude $|E_i|$) and the absolute error (with respect to the Maliuzhinets' formulation) for the TM and TE polarizations, respectively. The results for the TM polarization, illustrated in Figs. 2 and 4, demonstrate that the new soft coefficient proposed in Section II-D has a superior performance (with absolute errors smaller than 10 dB) and considerably improves the estimates in the backscattering region (i.e., $\phi_d \approx \phi_i$), where the other heuristic coefficients greatly fail, specially for $\phi_i = \pi/6$. For the TE (hard) polarization, the superior behavior can still be observed, except for $\phi_d < \pi/10$ in Fig. 3 and for $\phi_d > 5\pi/4$ in Fig. 5, where the heuristic hard diffraction coefficient proposed in [3] apparently is the best choice.

B. Scattering by a Lossy Cylinder With an Interior Wedge

The second case study considered here is the scattering by an infinite cylinder, which has the cross section depicted in Fig. 6. The source is an infinite electric (for the soft TM polarization) or magnetic (for the hard TE polarization) line current, located at T in Fig. 6. Observations are made along the dotted line illustrated in Fig. 6. Note that the source and observer locations are chosen so to stress the contribution of the diffraction by the cylinder internal wedge (see Fig. 6). The operation frequency is 1 GHz, and the obstacle electric characteristics are $\varepsilon_r = 7$ and $\sigma = 0.2$ S/m. Figs. 7 and 8 illustrate the total electric field $(E_{\rm t})$ normalized with respect to the electric field radiated by the line current at a distance of 1 m $(E_{\rm i})$ for the TM and TE polarizations, respectively. The results provided by the novel formulation of Section II-D are compared against the formulation proposed by Holm [4] and numerical estimates obtained by a method-of-moments (MoM) analysis [7] with losses accounted for by means of an impedance boundary condition (IBC) [6] with the obstacle electric characteristics ($\varepsilon_{\rm r}$ and σ). The results shown in Figs. 7 and 8 demonstrate that the proposed heuristic coefficients are appropriate to analyze the scattering by arbitrarily shaped cylinders, as the discrepancies observed are not superior to 0.5 dB for both polarizations.

C. Evaluation of the Novel Heuristic Diffraction Coefficients in an Urban-Like Scenario

The last case study is the scattering analysis through the scenario depicted in Fig. 9, which illustrates a plane view of the

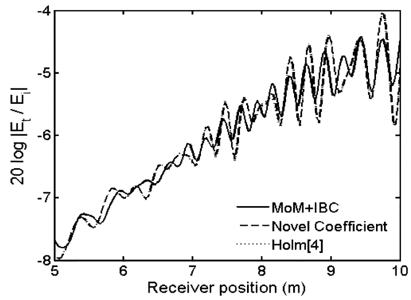

Fig. 8. TE electric field at the observation points depicted in Fig. 6.

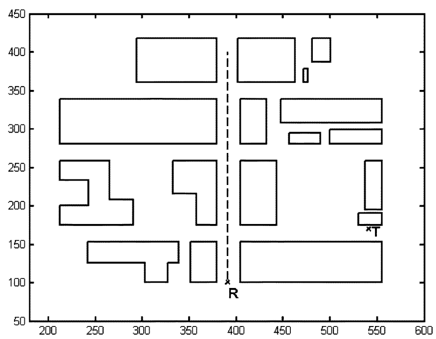

Fig. 9. Plane view of the core region of Ottawa, Canada. Receivers are located along Bank St.

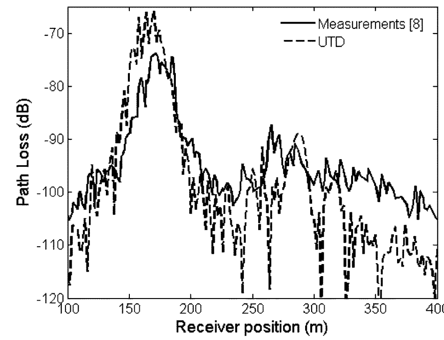

Fig. 10. Normalized electric field at receiver locations depicted in Fig. 9.

downtown core of Ottawa, Canada. Such a scenario was already investigated in [8] and [9], and measured data are available for comparison purposes. These measurements were made at 910 MHz, using transmitting and receiving antennas with heights of 8.5 and 3.65 m, respectively [8]. In the numerical simulations, the transmitter is a vertical infinitesimal electric dipole (i.e., *soft* polarization with respect to the obstacle wedges).

In order to handle such urban environment, a quasi-3-D ray-tracing algorithm was implemented, based on the image theory [10], [11]. All ray paths with a maximum of six reflections and two diffractions were considered to track the field from the transmitter (T) to the receivers (located along the Bank St. in Fig. 9). The quasi-3-D algorithm considers reflections over ground and the obstacle faces, but reflections or diffractions at the building tops are ignored. However, this is not a concern in this particular case study, as the transmitter and receiver heights are much smaller than the buildings heights [8], [9]. Losses are considered assuming that $\varepsilon_r = 7$ and $\sigma = 0.2$ S/m for the reflections and diffractions from obstacles (buildings) and $\varepsilon_r = 15$ and $\sigma = 0.05$ S/m for the reflections at ground [9].

Fig. 10 shows the path loss at the receiver locations, where the estimates obtained by the novel heuristic formulation of Section II-D are compared with the measured data of [8]. Once more, one can observe the usefulness of the proposed heuristic theory to handle complex scenarios and arbitrary transmitter and receiver locations.

IV. Conclusion

This work presented a novel heuristic soft and hard UTD coefficients for the analysis of the scattering by lossy wedges. The proposed coefficients combine features of previously derived heuristic coefficients [3], [4]. The novel heuristic coefficients provide superior performance in any region, particularly for TM scattering in deep shadow regions. Also, the coefficients are reciprocal and, consequently, suited to handle complex scenarios with arbitrarily located sources and observers.

To validate the proposed coefficients, three case studies were investigated. Initially, the scattering of a plane wave by a right-angle lossy wedge was analyzed, where several heuristic UTD coefficients were compared against an accurate analysis based on the Maliuzhinets' diffraction coefficients [6]. Then, the novel heuristic coefficients were compared against the MoM analysis of the scattering by a lossy cylinder with internal and external wedges. Finally, a real-life urban radio channel was characterized by the proposed heuristic formulation, with its performance compared against measurements [8]. All case studies illustrate and indicate the usefulness and applicability of the novel heuristic coefficients for the analysis of lossy wedges.

Acknowledgment

This work was supported in part by CNPq and CAPES, Brazil.

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Manuscript received October 27, 2006 (e-mail: schett@cpdee.ufmg.br).