Novel Heuristic UTD and TD-UTD Coefficients for the Analysis of Electromagnetic Scattering by Lossy Conducting Surfaces

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***Abstract* — In this work, novel heuristic coefficients are derived for the uniform theory of diffraction (UTD), both in frequency (FD-UTD) and time (TD-UTD) domains, in order to account for lossy wedges. In FD, the novel coefficients are appropriate to handle complex scenarios with arbitrary transmitter and receiver positions in an efficient and reciprocal manner. The new coefficients take advantage of two previously proposed heuristic coefficients, combining both in a novel approach. In TD, early-time approximations are employed to establish the coefficients suited for the analysis of short-pulse reflection and diffraction by dispersive obstacles.**

***Keywords* — Uniform theory of diffraction, heuristic diffraction coefficients, electromagnetic transient analysis, propagation through dispersive media.**

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]. Then, Luebbers established heuristic diffraction coefficients to account for lossy conducting wedges, suited for path loss predictions [2]. The concepts introduced by Luebbers were further extended by Aïdi and Lavergnat to define reciprocal coefficients [3]. Afterwards, Holm applied the Fresnel-Kirchhoff theory to propose a different heuristic coefficient with superior performance deep in the shadow region, where Luebbers's coefficient fails [4]. However, as in [2], Holm's coefficient does not obey reciprocity. Thus, our first aim is to apply the concepts introduced by Aïdi and Lavergnat [3] into Holm's coefficient [4], in order to establish an efficient and reciprocal diffraction coefficient for radio channel characterizations in the frequency domain, what will discussed in Sect.II-A. In order to estimate the usefulness and applicability of the proposed frequency domain (FD) UTD heuristic coefficients, diffractions by lossy wedges are investigated in Sect. III-A.

With the increse of communication services that require signals with large bandwidths, e.g., LMDS (Local Multipoint Distribution Services), a proper wideband characterization of the radio channel—typically in a urban scenario—prior to the service launch may be necessary. Such characterizations can be performed by means of time-domain (transient) analyses based on the propagation of short radio pulses from a transmitter (T) to a receiver (R). There are, at least, two different approaches to obtain the electromagnetic radiated field in time domain. One is to perform the analysis in the frequency domain (FD) for a wide frequency range and then apply an Inverse Discrete Fourier Transform (IDFT) to obtain the desired time domain analysis. The other is to conduct the electromagnetic field analysis directly in time domain (TD). FD solutions, together with IDFT techniques, are very time consuming for the analysis of large bandwidth signals. TD (transient) analysis is then more adequate to wideband characterizations, since the whole electromagnetic channel response can, in principle, be evaluated at once from the analysis of the propagation of a short pulse. Besides, it is more natural to perform the transient analysis directly in TD. So, here, the time domain (TD) UTD will be adopted to perform transient analyses of the scattered electromagnetic waves. The TD-UTD was originally developed to analyze scattering by perfect electric conductors (PEC) [5]. Our second objective in this paper is to extend the TD-UTD to the analysis of lossy obstacles (i.e., obstacles with finite conductivities), in order to provide a more realistic wideband characterization of urban radio channels. The heuristic TD-UTD is presented in Sect.II-B and then exemplified in Sect. III-B in the analysis of a short-pulse propagation through a urban-like environment comprising several lossy obstacles.

Both FD-UTD and TD-UTD employs ray-tracing techniques to determine the optical paths between source and observer.

II. HEURISTIC UTD COEFFICIENTS FOR LOSSY WEDGES

A. *Novel FD-UTD Heuristic Diffraction Coefficients for Lossy Conducting Wedges*

The novel FD-UTD 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.

According to [4], but adopting the classical notation of [1], the proposed heuristic diffraction coefficient is given by:

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$$D^{s,h} = G^{s,h}\left\{\left[W_n^{s,h} D_1 + R_n^{s,h}(\alpha_n) D_3\right] + \left[W_0^{s,h} D_2 + R_0^{s,h}(\alpha_0) D_4\right]\right\}, \tag{1}$$

where D_i, for i=1,…,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

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

where,

$$\hat{\varepsilon}_r = \varepsilon_r - j\sigma/(\omega\varepsilon_0) \tag{3}$$

is the wedge complex relative permittivity. $G_0^{s,h}$ and $G_n^{s,h}$ are used when grazing incidence occurs and are defined as:

$$\begin{cases} G^{s,h} = 1/2, \ \phi_i = 0 \ \text{or} \ \phi_i = n\pi \\ G^{s,h} = 1, \quad \text{otherwise} \end{cases}, \tag{4}$$

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). W_n and W_0 are defined as:

$$W_n^{s,h} = \begin{cases} R_0^{s,h}(\alpha_0) R_n^{s,h}(\alpha_n), & \phi_i < n\pi/2 \\ 1, & \phi_i \geq n\pi/2 \end{cases}$$
$$W_0^{s,h} = \begin{cases} 1, & \phi_i < n\pi/2 \\ R_0^{s,h}(\alpha_0) R_n^{s,h}(\alpha_n), & \phi_i \geq n\pi/2 \end{cases} \tag{5}$$

The results in [4] indicate that Holm's coefficients provide superior results than Luebbers' ones [2]. But 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 defining the incidence angles α_0 and α_n as [3]:

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

B. *Novel TD-UTD Heuristic Diffraction Coefficients for Finite Conductivity Wedges*

In communications, the most significant contributions to the transient field occur at the time interval close to the arrival of each wavefront (early time) [6]. As the behavior of the transient field, just after the arrival of the wavefront, is governed by the high-frequency field components, early-time solutions are, consequently, associated with high-frequency components, while late-time solutions correspond to lower frequencies [6]. So, early-time solutions can be successfully obtained from asymptotic techniques, such the TD-UTD [5].

The TD-UTD coefficients were derived by Rousseau and Pathak for early-time scattering by perfectly conducting wedges [5]. The extension of the TD-UTD to the analysis of lossy obstacles will be performed by the application of the analytic time transform (ATT) to FD-UTD heuristic coefficients presented in Sect.II-A, used to account for losses in the frequency domain. Extending the notation of (1), the FD-UTD coefficients can be fully written as:

$$\begin{aligned} D_{s,h}(\phi,\phi';\omega) = {} & \frac{-e^{-j\pi/4}}{2n\sqrt{2\pi k}\sin\beta_0} \times G^{s,h} \\ & \left\{ W_n^{s,h} \cot\left(\frac{\pi + (\phi - \phi')}{2n}\right) F[kLa^+(\phi - \phi')] + \right. \\ & W_0^{s,h} \cot\left(\frac{\pi - (\phi - \phi')}{2n}\right) F[kLa^-(\phi - \phi')] + \\ & R_{s,h}(\alpha)\left[\cot\left(\frac{\pi + (\phi + \phi')}{2n}\right) F[kLa^+(\phi + \phi')] + \right. \\ & \left.\left. \cot\left(\frac{\pi - (\phi + \phi')}{2n}\right) F[kLa^-(\phi + \phi')]\right]\right\}, \end{aligned} \tag{7}$$

where n, $sin(\beta_0)$, ϕ, ϕ' and $F(.)$ are defined in [1]. As can be seen from (7), such heuristic coefficients involve the Fresnel reflection coefficients R_s and R_h (2), functions of the complex permittivity $\hat{\varepsilon}_r$ of the lossy obstacle. The ω dependence of $\hat{\varepsilon}_r$ and, consequently, of the Fresnel coefficients prevent the attainment of close-form analytical TD-UTD coefficients by the ATT [5]. This drawback is not present in the analysis of the scattering by PEC's, as the reflection coefficients are constant.

However, our aim is to obtain a heuristic TD-UTD for the analysis of early-time scattering. Consequently, only the high-frequency components of the scattered field have to be considered. From (3), one observes that in the limit $\omega \to \infty$ the imaginary part of the complex permittivity vanishes (i.e., $\hat{\varepsilon}_r \approx \varepsilon_r$, with negligible frequency variation). So, our approach is to ignore the variation of the permittivity with ω, and, consequently, to assume that the Fresnel reflection coefficients do not vary with ω. If so, it is now possible to obtain a close form evaluation of the ATT of the FD-UTD formulation, yielding the desired heuristic TD-UTD. It is important to note that the assumption of a constant $\hat{\varepsilon}_r$ is in agreement with the early-time aspects of the scattering from lossy obstacles, as dispersive effects are negligible in high frequencies [6].

Assuming that for early times the Fresnel reflection coefficients do not vary with ω, the heuristic TD-UTD coefficients for lossy wedges are given by:

$$\overset{+}{\overline{D}}_{s,h}(\phi,\phi',\mathrm{t}) = \frac{-1}{2n\sqrt{2\pi}\sin\beta_0}\times$$
$$\left\{W_n^{s,h}\cot\left(\frac{\pi+(\phi-\phi')}{2n}\right)G(x_1)+W_0^{s,h}\cot\left(\frac{\pi-(\phi-\phi')}{2n}\right)G(x_2)\right.$$
$$\left.+R_{\mathrm{s,h}}\left[\cot\left(\frac{\pi+(\phi+\phi')}{2n}\right)G(x_3)+\cot\left(\frac{\pi-(\phi+\phi')}{2n}\right)G(x_4)\right]\right\} \tag{8}$$

where $G(x,t)$ and $x_{1,\ldots,4}$ are defined in [5].

III. CASE STUDIES

A. Novel FD-UTD Heuristic Coefficients Analyses

In order to demonstrate the usefulness of the proposed FD-UTD formulation, three case studies will be presented.

Initially, the several heuristic coefficients (i.e., Luebbers [2], Aïdi and Lavergnat [3], Holm [4] and the novel coefficients proposed) are compared to each other in the analysis of the scattering of a plane wave by a right-angle lossy wedge with geometrical parameters depicted in Fig. 1 is analyzed. Both TM (soft) and TE (hard) polarizations are considered and an accurate asymptotic diffractive analysis based on Maliuzhinets' coefficients [7] is adopted as reference for the comparative study. For both TM and TE plane-wave polarizations, the direction of incidence ϕ_i = /π6, as illustrated in Fig. 1. The operation frequency is 1GHz and the observations are made at a distance of 30λ from the edge, with the observation direction ϕ_d varying from 0 to 3/π2 (see Fig. 1). Figures 2 and 3 show the relative diffracted electric field amplitude |*Ed*| (with respect to the incident electric field amplitude |*Ei*|) and the absolute error (with respect to the Maliuzhinets' formulation) for the TM and TE polarizations, respectively.

Then, the novel heuristic coefficients are compared against the MoM [8] analysis of the scattering by a lossy cylinder with the cross section depicted in Fig. 4. The source is an infinite line current, located at T and observations are made along the dotted line illustrated in Fig. 4. The results shown in Figs. 5 and 6 demonstrate that the proposed heuristic coefficients are appropriate to analyze the scattering by arbitrarily shaped cylinders, as the discrepancies observed are not superior to 0.5dB for both polarizations.

The last case study is the scattering analysis through the scenario depicted in Fig. 7, which illustrates a plane view of the downtown core of Ottawa city, Canada. A real-life urban radio channel was characterized by the proposed heuristic formulation, with its performance compared against measurements given in [9]. These measurements were made at 910MHz, using transmitting and receiving antennas with heights of 8.5m and 3.65 m, respectively [8]. In the numerical simulations, the transmitter is an infinitesimal electric dipole with a vertical polarization with respect to ground (i.e., *soft* polarization with respect to the obstacle wedges). A quasi-3D

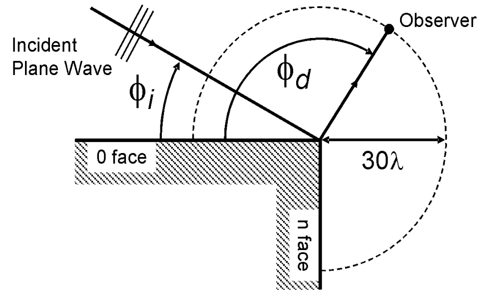

Fig. 1. Right-angle lossy wedge with ε_r = 10 and σ = 0.01 S/m.

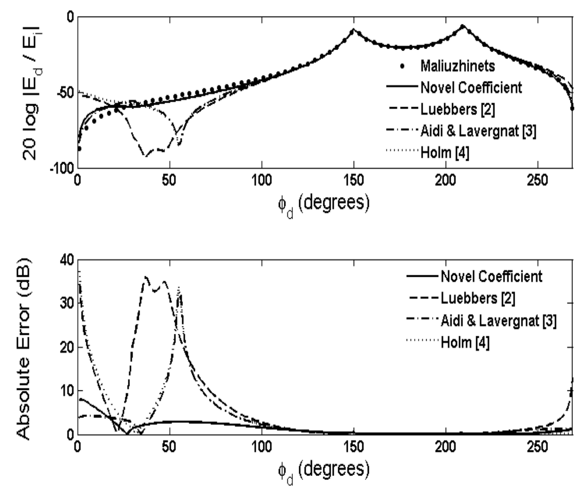

Fig. 2. TM diffracted field around the wedge of Fig. 1.

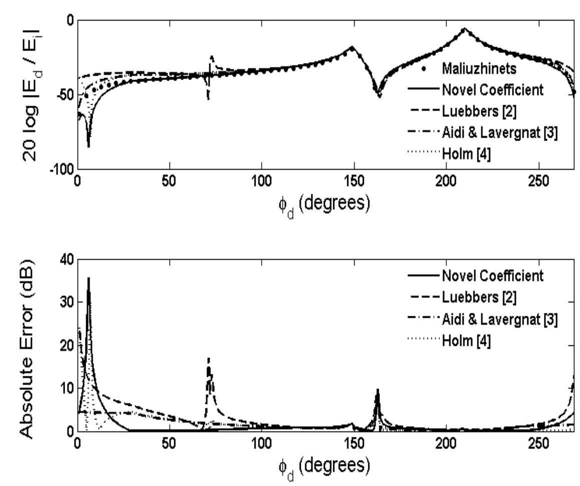

Fig. 3. TE diffracted field around the wedge of Fig. 1.

ray-tracing algorithm was implemented, based on the image theory, in order to determine the ray-paths with a maximum of 6 reflections and 2 diffractions, to track the field from the transmitter (T) to the receivers (located along the dotted line in Fig. 7). Figure 8 shows the path loss at the receiver locations, obtained by the novel heuristic formulation and by the measured data presented in [8]. One can observe the usefulness of the proposed heuristic theory to handle complex scenarios and arbitrary transmitter and receiver locations.

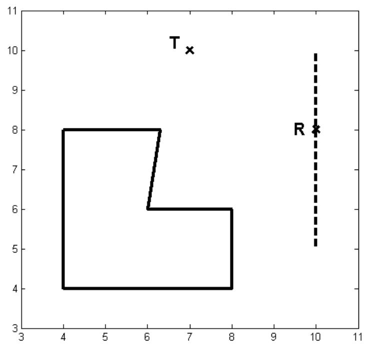

Fig .4. Environment obstacles with $\varepsilon_r = 7$ and $\sigma = 0.2$ S/m.

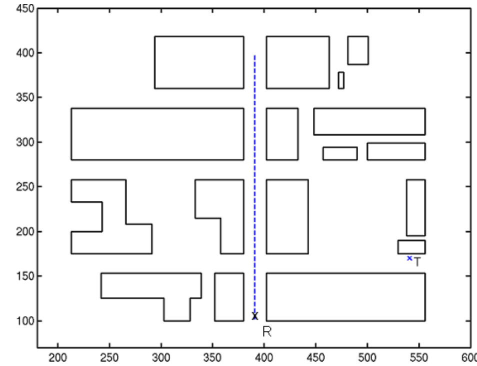

Fig .7. Plane view of the core region of Ottawa, Canada. Receivers are located along the dotted line.$\varepsilon r = 7$ and $\sigma = 0.2$ S/m for the obstacles (buildings) and $\varepsilon r = 15$ and $\sigma = 0.05$ S/m for the ground.

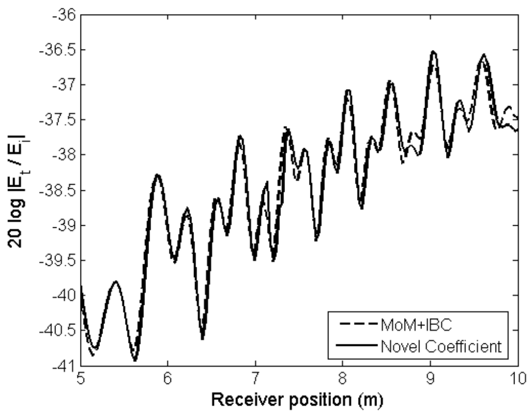

Fig. 5. TM normalized electric field at the observation points depicted in Fig. 4.

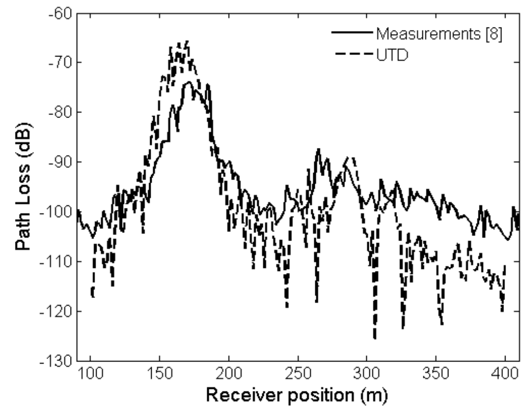

Fig. 8. Normalized electric field at the receiver locations depicted in Fig. 7.

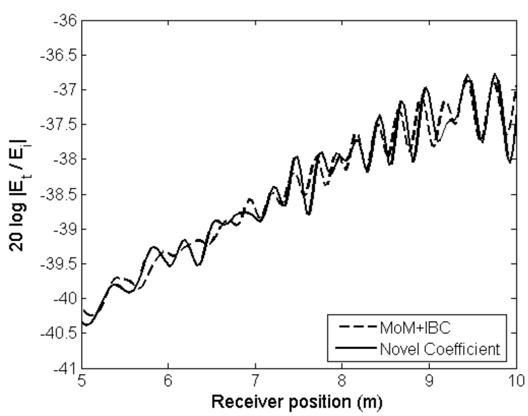

Fig. 6. TE normalized electric field at the observation points depicted in Fig. 4.

B. Novel TD-UTD Heuristic Coefficients Analyses

In order to investigate the applicability of the heuristic TD-UTD formulation proposed, the scenario of Fig. 9 has been analyzed. A short pulse of approximately 1ns of duration is radiated from an infinite electric current line at T. The sides of the square obstacles and the distances between two consecutive obstacles are equal to 25λ, where λ is the wavelength at the central frequency of the pulse spectrum [5]. Figures 10, 11 and 12 present the electric field amplitude at the receiver, obtained by TD-UTD based formulations and also by the FD-UTD with results converted to time domain by an inverse discrete Fourier transform (IDFT), as a reference result. In Fig. 10, both TD and FD+IDFT results were obtained considering perfect electric conductor (PEC) obstacles. From the figure, one observes that both techniques essentially provide the same results, as expected. In Fig. 11, we compare the PEC TD-UTD results previously depicted in Fig. 10 with a heuristic FD-UTD+IDFT analysis assuming lossy obstacles, in order to establish the necessity of considering losses in real-life problems. For the FD-UTD+IDFT analysis all obstacles have er=7.0 and s=0.2 S/m, which are typical values for building walls at VHF. From the figure one observes that losses attenuate the field by a factor of approximately 10 when compared with the PEC scenario. Finally, Fig. 12 illustrates the results provided by the heuristic TD-UTD for lossy obstacles (8), compared with the FD-UTD+IDFT analysis already depicted in Fig. 11. The difference between them is about 10%, with the heuristic TD-UTD tending to underestimate the FD-UTD+IDFT.

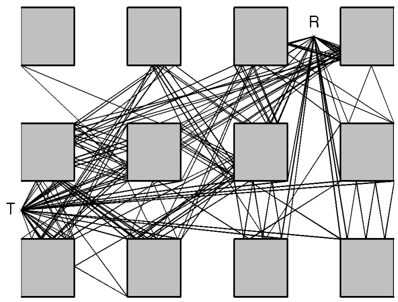

Fig. 9 Two-dimensional scenario of the TD-UTD analysis.

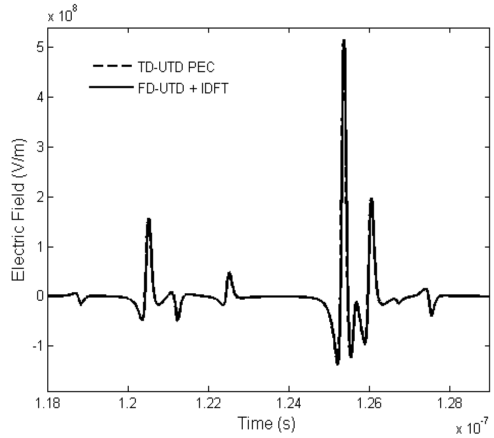

Fig. 10. Electric field amplitude at R, provided by the TD-UTD and the FD-UTD+IDFT, assuming PEC obstacles.

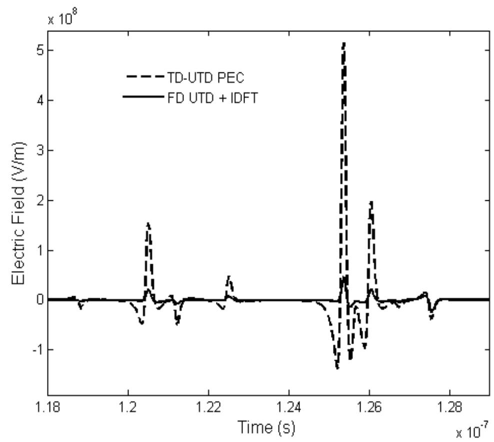

Fig. 11. Electric field amplitude at R, provided by the TD-UTD (for PEC obstacles) and the FD-UTD+IDFT(for lossy obstacles).

IV. Conclusions

This work presented a novel heuristic soft and hard UTD coefficients for the analysis of the scattering by lossy wedges both in frequency and time domains.

The novel heuristic FD coefficients combine features of previously derived heuristic coefficients [3], [4], and they

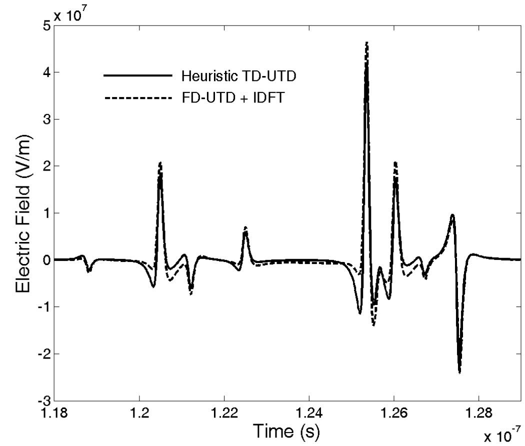

Fig. 12. Electric field amplitude at R, provided by the heuristic TD-UTD and the FD-UTD+IDFT, assuming lossy obstacles.

provided superior performance in any region, particularly for TM scattering. Also, the coefficients are reciprocal and, consequently, suited to handle complex scenarios with arbitrarily located sources and observers. To validate the proposed formulation, three case studies were investigated, where all of them illustrate and indicate the usefulness and applicability of the novel heuristic coefficients for the analysis of lossy wedges.

A heuristic TD-UTD formulation was derived for the early-time analysis of the wideband scattering by lossy obstacles. The formulation was derived from the ATT of a heuristic FD-UTD formulation, together with appropriate early-time assumptions. Case studies comprising the scattering by several lossy objects demonstrate the applicability and usefulness of the proposed technique.

V. References

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