A Novel Symmetrical Heuristic Coefficient for Urban Microcellular Environments

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***Abstract*—A novel heuristic diffraction coefficient is presented which is perfectly reciprocal and symmetrical. The prediction obtained using proposed coefficient is compared with that obtained using rigorous Maliuzhinets' solution. It is shown that the proposed coefficient is more efficient than available diffraction coefficient. The comparison is made for both soft and hard polarization. Further, the applicability of proposed coefficient in complex urban scenario is demonstrated by applying the coefficient in the city of Ottawa.**

***Index Terms*—Deterministic propagation model, microcellular scenario, ray tracing, uniform theory of diffraction (UTD).**

I. Introduction

Geometrical theory of diffraction (GTD) [1] and Uniform theory of diffraction (UTD) [2] are high frequency asymptotic solution to the problem of diffraction by a wedge. The modeling of wireless propagation channel based on deterministic approach is usually performed using Geometrical theory of diffraction (GTD) and its extension uniform theory of diffraction (UTD) [1], [2]. GTD gives fair prediction of the diffracted field at the points away from the shadow boundaries but fails to predict the field at the shadow boundaries. Uniform theory of diffraction which is an extension of GTD is based on Clemmow method of steepest descent gives continuous field at the boundaries (though not accurate). In order to make the UTD applicable for lossy dielectric wedge, this is modified by Luebbers [3] by heuristically incorporating Fresnel reflection coefficient as a multiplying factor to the components of diffraction coefficient. As a result, the coefficient becomes applicable for dielectric wedge. However, it lacks accuracy in certain region such as shadow region (e.g. See [4], Fig.13, 14). Holm [5] proposed modification of the original Luebbers coefficient by modifying the multiplying factors to be used in the coefficient. This resulted in the improvement in the accuracy of shadow region. However, Holm's coefficient lacked accuracy in the illumination region. The modification to Luebbers formulation was proposed by Kate A. Remley et al. [4] who modified the angles to be used in the calculation of Reflection coefficient. As a result, this improved the accuracy in the shadow region. Modification to the Holm's coefficient was proposed by El-Sallabi et al. [6]. In this, for exterior and interior wedge both, the angle definition used in Fresnel reflection coefficient in the calculation of diffraction coefficient were defined extensively. They show good agreement with the rigorous Maliuzhinets solution. However, these coefficients were neither reciprocal nor symmetrical. In [7], a reciprocal heuristic coefficient was defined that used the angle definition proposed by Aidi et al. [9] and showed good agreement over other available coefficients. However, this showed the reciprocity property only when the transmitter (Tx) and the receiver (Rx) were either side of the wedge. When the Tx and Rx were both on the same side, it was not reciprocal. Moreover, it does not show symmetry property.

The present work proposes the heuristic diffraction coefficient which is perfectly reciprocal and symmetrical. Moreover, it is shown that the coefficient is more efficient over the other available diffraction coefficients. In order to validate the coefficient, the comparison is done with rigorous Maliuzhinets coefficient and available measurement.

The paper is organized as follows. The section-II gives the problem formulation and brief description of available heuristic coefficient. Section-III deals with the proposed solution and detailed discussion of the reciprocal and symmetrical property of diffraction coefficient. Section-IV deals with the results and discussion followed by conclusion.

II. Available Heuristic Diffraction Coefficient

The problem of diffraction from the dielectric wedge can be observed in Fig. 1. The source is at the distance r_1 from the wedge tip and the observation point is at the distance r_2 from the tip. The angle to the incident ray and the diffracted ray from the 0-face are ϕ and ϕ' respectively. The diffracted field at the observation point is given as

$$E(r) = \frac{E_0}{r_1} D \sqrt{\frac{r_1}{r_2(r_1+r_2)}} \exp(-jk(r_1+r_2)) \tag{1}$$

where E_0 the transmitted field at the transmitter and D is the diffraction coefficient of the wedge. For perfect electrical conducting wedge (PEC), the diffraction coefficient proposed by Pathak et al. [2] is given by

$$D_{S,h} = -\frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}} (D_1 + D_2 \mp (D_3 + D_4)) \tag{2}$$

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$$D_i = \cot \beta_i \times F[kLX_i], i = 1,......4 \tag{3}$$

$$\beta_1 = \frac{\pi + (\phi - \phi')}{2n} \quad , \quad X_1 = a^+(\phi - \phi') \tag{4}$$

$$\beta_2 = \frac{\pi - (\phi - \phi')}{2n} \quad , \quad X_2 = a^-(\phi - \phi') \tag{5}$$

$$\beta_3 = \frac{\pi + (\phi + \phi')}{2n} \quad , \quad X_3 = a^+(\phi + \phi') \tag{6}$$

$$\beta_4 = \frac{\pi - (\phi + \phi')}{2n} \quad , \quad X_4 = a^-(\phi + \phi') \tag{7}$$

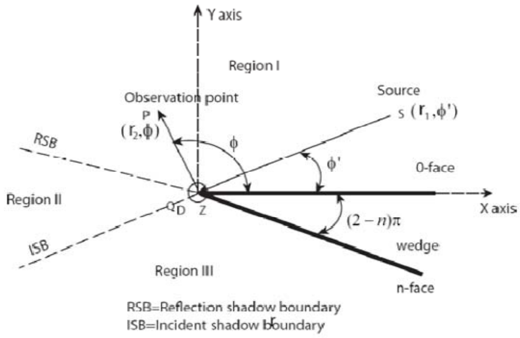

Fig. 1. An illustration of diffraction by dielectric wedge.

For lossy dielectric wedge, Luebbers modified (2) by using multiplying factors as follows

$$D_{S,h} = -\frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}}(D_1 + D_2 + R_n^{s,h} D_3 + R_0^{s,h} D_4) \tag{8}$$

where $R_0^{s,h}$ and $R_n^{s,h}$ are the Fresnel reflectionCoefficient for 0-face and n-face respectively. Superscripts s and h stand for soft and hard polarization respectively

$$R^s = \frac{\sin\theta - \sqrt{\varepsilon - \cos^2\theta}}{\sin\theta + \sqrt{\varepsilon - \cos^2\theta}} \tag{9}$$

$$R^h = \frac{\varepsilon\sin\theta - \sqrt{\varepsilon - \cos^2\theta}}{\varepsilon\sin\theta + \sqrt{\varepsilon - \cos^2\theta}} \tag{10}$$

Here, θ_0 = min (ϕ', ϕ), and θ_n = min ($n\pi - \phi'$, $n\pi - \phi$).Holm [5] rearranged the multiplying factors to obtain better performance than Luebber's diffraction coefficient in the deep shadow region. The Holm's heuristic diffraction coefficient is
given as

$$D_{S,h} = -\frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}}(R_n^{s,h} R_0^{s,h} D_1 + D_2 + R_n^{s,h} D_3 + R_0^{s,h} D_4) \tag{11}$$

Here, R_0, R_n are calculated based on (9),(10).Daniela et al. [7] modified the work of Holm's diffraction coefficient by making it reciprocal. The Daniela's coefficient for soft and hard polarizations are given by

$$D_{S,h} = -\frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}}(M_n^{s,h} D_1 + M_0^{s,h} D_2 + R_n^{s,h} D_3 + R_0^{s,h} D_4) \tag{12}$$

where

$$M_n^{s,h} = \begin{cases} R_n^{s,h} R_0^{s,h} & \phi' \le \frac{n\pi}{2} \\ 1 & \phi' \ge \frac{n\pi}{2} \end{cases} \tag{13}$$

$$M_0^{s,h} = \begin{cases} 1 & \phi' \le \frac{n\pi}{2} \\ R_n^{s,h} R_0^{s,h} & \phi' \ge \frac{n\pi}{2} \end{cases} \tag{14}$$

Here, Fresnel reflection coefficient, R_0, R_n are calculated with angle θ_0 and $\theta_n$as per angular definition of Aidi and Lavergnat [9] given as

$$\theta_0 = \theta_n = \min(\phi', \phi, n\pi - \phi', n\pi - \phi) \tag{15}$$

It may be noted that the above diffraction coefficient is reciprocal when Tx and Rx are opposite side of the wedge

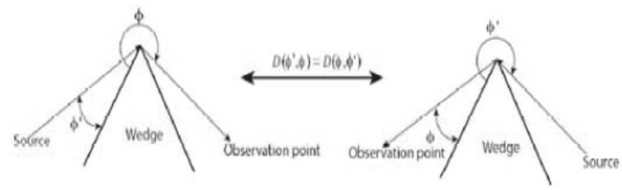

Fig. 2. Reciprocal condition of diffraction coefficient.

III. Reciprocal and Symmetrical Property of Diffraction Coefficient

Diffraction coefficient is reciprocal if exchanging the position of the transmitter and the receiver does not alter the value of the diffraction coefficient. The condition is shown in Fig. (2). Hence,

$$D(\phi, \phi') = D(\phi', \phi) \tag{16}$$

Considering the formulation of diffraction coefficient in (2) to (7), we note that exchanging ϕ by ϕ' results in $D_1 \leftrightarrow D_2$ and D_3, D_4 remain unaltered. Therefore, our multiplying factors of D_1, D_2 should get interchanged with $\phi \leftrightarrow \phi'$ and multiplying factors of D_3, D_4 should remain unchanged to make diffraction coefficient perfectly reciprocal.

Similarly, diffraction coefficient is said to be symmetrical if the value of the diffraction coefficient remains same irrespective of the 0-face or n-face is taken as the reference face for angle measurement (See Fig. 3). Hence

$$D(\phi, \phi') = D(n\pi - \phi, n\pi - \phi') \tag{17}$$

In the expression of (2), it may be noted that with $\phi \leftrightarrow n\pi - \phi$ and $\phi' \leftrightarrow n\pi - \phi'$ results in $D_1 \leftrightarrow D_2$ and $D_3 \leftrightarrow D_4$ As results, the multiplying factors of these components pair should get interchanged to ensure symmetry property of the diffraction coefficient

IV. Proposed Diffraction Coefficient

In the proposed diffraction coefficient, we divide the exterior angle of the dielectric wedge in the three region based on the position of the reflection shadow boundary (RSB) for 0-face and n-face. Our proposed diffraction coefficient is as follows:

$$D_{S,h} = \frac{e^{-j\frac{\pi}{4}}}{2n\sqrt{2\pi k}}(M_1D_1 + M_2D_2 + M_3D_3 + M_4D_4) \tag{18}$$

For reciprocal condition $M_1 \leftrightarrow M_2$ and $M_3 = M_4$. For symmetrical property to be satisfied, we need $M_1 \leftrightarrow M_2$ and $M_3 \leftrightarrow M_4$ these two conditions can be satisfied simultaneously when $M_1 \leftrightarrow M_2$ and $M_3 = M_4$. Thus, we set multiplying factors M_i , i= 1,…, 4 as described as in Table-I

In addition to that, for region-I,

$$\theta_0 = \theta_n = \min(T_1, T_2) \tag{19}$$

Where $T_1 = \frac{\pi}{2} - |\frac{\pi}{2}, \phi'|$ and $T_2 = \frac{\pi}{2} - |\frac{\pi}{2}, \phi|$

in Region-II,

$$\theta_0 = \theta_n = \min(\phi', \phi, n\pi - \phi', n\pi - \phi) \tag{20}$$

TABLE I: Multiplying Factor to the Proposed Diffraction Coefficient

Region-I,II,III	
$\phi > \phi'$	$\phi < \phi'$
$M_1 = R_0(\theta_0) R_n(\theta_n)$	$M_1 = 1$
$M_2 = 1$	$M_2 = R_0(\theta_0) R_n(\theta_n)$
$M_3 = R_0(\theta_0)$	$M_3 = R_0(\theta_0)$
$M_4 = R_n(\theta_n)$	$M_4 = R_n(\theta_n)$

in Region-III,

$$\theta_0 = \theta_n = \min(T_3, T_4) \tag{21}$$

$$T_4 = \frac{\pi}{2} - |\frac{\pi}{2}, (n\pi - \phi)| \tag{22}$$

$$T_3 = \frac{\pi}{2} - |\frac{\pi}{2}, (n\pi - \phi')| \tag{23}$$

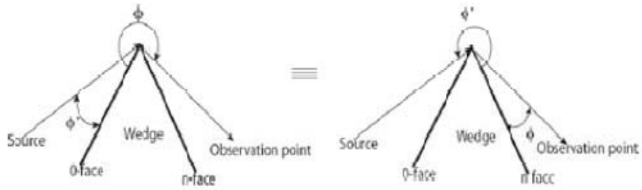

Fig. 3. Symmetrical condition of diffraction coefficient

V. Result and Discussion

A. *Symmetrical and Reciprocal Property Verification of the Diffraction Coefficient*

In this section, we consider the symmetrical property of the proposed coefficient. For this case, we consider a dielectric right-angle wedge. The incident angle of the ray that illuminates the tip of wedge is 135^0 and the receiver moves in the circle of 2m with an increment of 1^0. In the first case, the angle measurement is done with respect to 0-face and in the second case; it is measured with respect to the n-face. The result is shown in Fig. 4. Similarly, for reciprocal property, the incident angle is chosen to be and in the first case, incident angle is held constant to be 45^0 and observation point is moved in a circle of the radius 2m. The sample interval is chosen to be 2^0. In both the cases, hard polarization has been considered. The result is shown in Fig. 5.

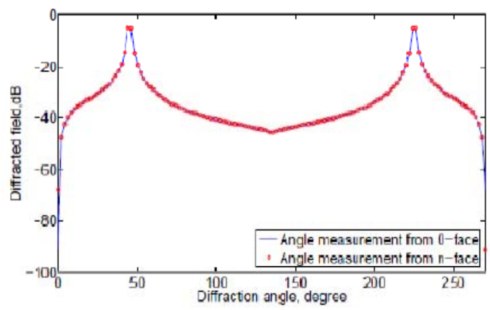

Fig. 4. Comparison of diffraction field obtained from the angle measurement from 0-face and n-face.

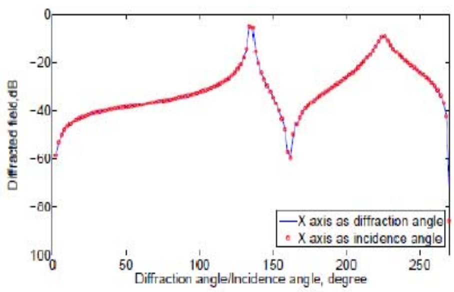

Fig. 5. Comparison of diffraction fields obtained from interchanging the position of T_X and R_X .

B. *Comparison of Diffraction Coefficient with Rigorous Maulizhinets Coefficients.*

In this section, our objective is to show the usefulness of the proposed diffraction coefficient. The comparison of proposed diffraction coefficient is done with rigorous Maliuzhinets diffraction coefficient [8] and Holm's diffraction coefficient [5]. The wedge is characterized with conductivity σ = 0:005 S/m and permittivity ε_r = 6. The distance of source and observation point was taken to be 3m each from the tip of wedge. Keeping the source at given angle, the observation point was moved at the step of 2^0 to obtain diffracted field. For comparison purpose, the wedge angle is chosen to be 10^0 and 90^0. Both the parallel and perpendicular polarizations are considered. Fig. 6 and Fig. 7 show the diffracted field pattern for the 10^0 wedge and incident angle 45^0 with both parallel and perpendicular polarizations. Here, a clear improvement can be seen in illumination region where Holm is differing from Maliuzhinets coefficient. Fig. 8 and Fig. 9 are for the 90^0 wedge and incidence angle 45^0. In this scenario, the novel coefficient gives good agreement with rigorous Maliuzhinets' solution viz-a-viz Holm's coefficient.

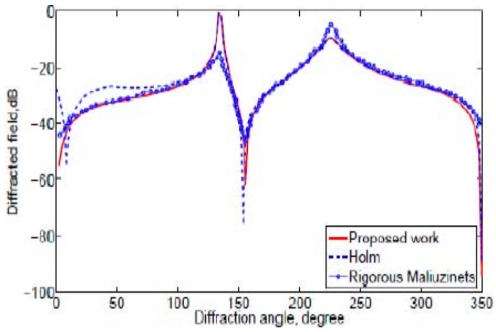

Fig. 6. Comparison of proposed diffraction coefficient with available diffraction coefficient and Rigorous Maulizhinets' solution [8]: Incident angle is 45^0 and wedge angle is 10^0, parallel polarization.

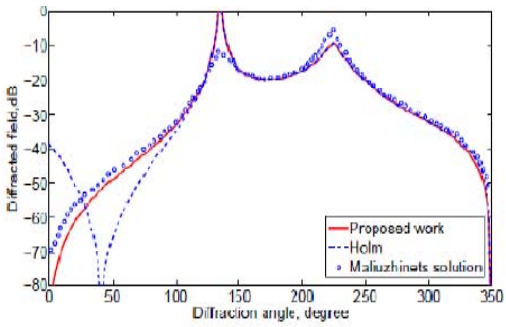

Fig. 7. Comparison of proposed diffraction coefficient with available diffraction coefficient and Rigorous Maulizhinets' solution [8]: Incident angle is 45^0 and wedge angle is 10^0, perpendicular polarization.

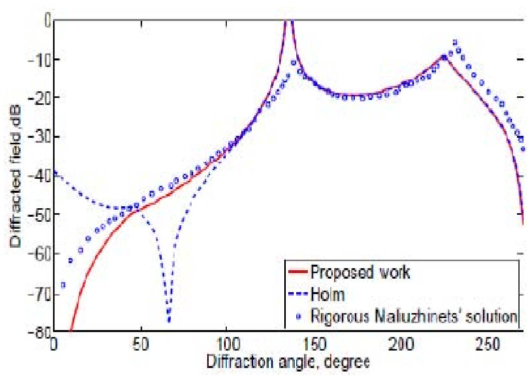

Fig. 8. Comparison of proposed diffraction coefficient with available diffraction coefficient and Rigorous Maulizhinets' solution [8]: Incident angle is 45^0 and wedge angle is 90^0, parallel polarization.

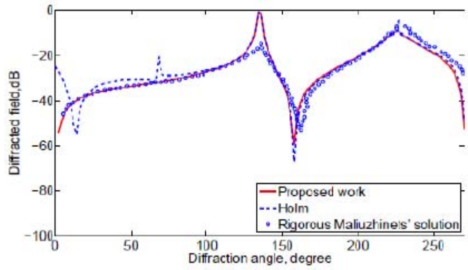

Fig. 9. Comparison of proposed diffraction coefficient with available diffraction coefficient and Rigorous Maulizhinets' solution [8]: Incident angle is 45^0 and wedge angle is 90^0, perpendicular polarization.

C. *Application of Proposed Diffraction Coefficient in Arbitrary Complex Urban Scenario.*

In this section, we will validate the applicability of proposed diffraction coefficient in a complex urban scenario of Ottawa city. in our analysis, we took microcellular environment (Ottawa City) for which measurement was carried out by James H. Whitteker [10]. In particular region (core) of this city, there are 15 buildings and total 72 walls (See Fig.10). This urban scenario is presented in 2D view in [[10], Fig. 2].

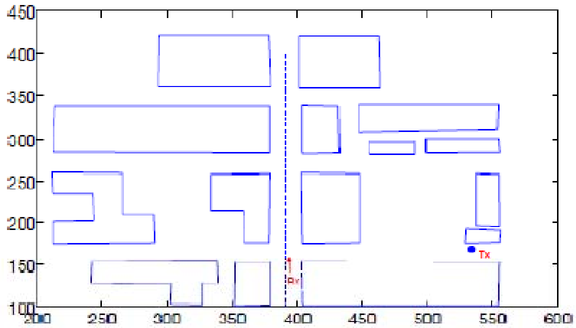

Fig. 10. Map of Ottawa city.

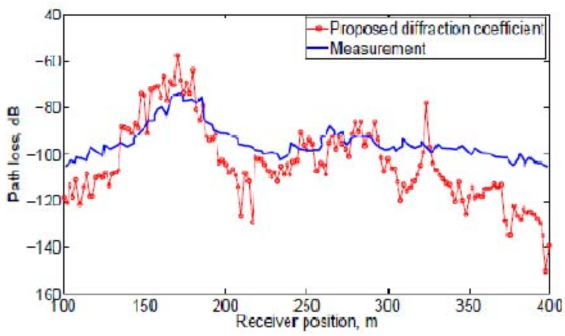

Fig. 11. Comparison of path loss prediction obtained by proposed diffraction coefficient with available measurement [10].

The measurement was carried out along the Bank St. and Tx is at 263 Laurier St. Frequency of operation is 910 MHz. The conductivity and permittivity of wall material were chosen to be σ = 0:001 S/m and ε_r = 7. The value of ε_r is consistent with the range $5 \leq \varepsilon_r \leq 7$ by direct measurement [11] and the value of σ is consistent with [12]. To obtain the path loss prediction, image-based ray tracing engine was set to 3 reflections and 2 diffractions. The prediction result is shown in Fig. 11. The result shows the usefulness of the proposed diffraction coefficient to handle arbitrary complex scenario.

VI. CONCLUSION

In this paper, we have presented a novel heuristic diffraction coefficient which is perfectly symmetrical and reciprocal. The proposed coefficient is validated by comparing it with rigorous Maliuzhinets solution, Holm's heuristic diffraction coefficient. Both the parallel and perpendicular polarizations have been considered. It is noted that the proposed coefficient is more accurate in illumination region and agrees well with Holm' coefficient and Maliuzhinets solution in shadow region. Further, the coefficient has been applied in the complex urban scenario of the Ottawa city and its usefulness has been demonstrated to handle such a complex scenario.

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