Modified Reflection Coefficient for Use in Mobile Path Loss Calculations

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Abstract- In this paper the reflection coefficient of electromagnetic wave incidence on the walls of the buildings and obstacles that occurs in mobile communication path was modified by solving the Riccati nonlinear equations. For this purpose, the building walls are assumed inhomogeneous layers where their permittivity changes as function of the wall thickness. Using this reflection coefficient, a new propagation model based on UTD and GTD (uniform geometrical theory of diffraction and geometrical theory of diffraction) for multiple diffraction paths is proposed. Using this model, the diffraction loss as well as the path loss for a row of buildings with two inhomogeneous faces are calculated and compared with measured data. Comparison of theoretical and measured results reveals that the modified reflection coefficient can adequately predict the reflective properties of the building walls. Moreover, results obtained with the proposed UTD model are in good agreement with the measurement data. Therefore, the modified reflection coefficient as well as the new UTD model can be used for estimation of multipath signals strength, diffraction loss and also path delay in ray tracing algorithms used in mobile communication, radar and radio links.

Keywords: Mobile Communication, Path Loss Prediction, UTD/GTD, Higher Order Diffraction Coefficient, Multiple Diffraction and Inhomogeneous Medium.

1. Introduction

With the rapid development of radio communications including cellular, wireless and portable communication, radio waves from HF to microwave bands are now in use everywhere. However, the attenuation of radio wave caused by reflection and diffraction from the buildings and obstacles in the radio path lead to sever problems in the communication channel. Therefore, in designing such links the prediction of received signal for optimum estimation of transmitter power, receiver noise, antenna gain, position of the base stations and characteristics of handset is very important. However in order to predict the attenuation caused by buildings and obstacles, different methods such as ray tracing, GTD/UTD and physical optics (P.O) which are high frequency and asymptotic solutions of Maxwell equations have been used [1-3]. Even though these approaches are high frequency approximation, but they are relatively efficient for field estimation in cellular mobile communication, radar and radio link design.

The ray tracing method assumes that the electromagnetic field is the sum of individual contributions associated with the rays and accordingly the received signal is sum of direct, reflection and diffraction rays [2]. Also it can be easily shown that in P.O. the received fields are related to the reflection coefficient in a direct manner. Therefore, ray tracing, GTD/UTD and P.O. approaches are based on the coefficients of diffracted and reflected rays. So the accuracy of the field estimation directly relates to these coefficients. However, up to now many researchers have studied these coefficients and tried to modify them for different surface, especially there are many approaches for modification of the diffraction coefficient [3-6]. It can be argued that in path loss estimation, the reflection coefficients are at least as important as the diffraction coefficients.

Moreover most of the reflection coefficients used in ray-tracing, UTD/GTD and P.O. are based on first-order reflection coefficient (Fresnel reflection coefficient) but as it is known the first-order reflection coefficient at most can predict the reflected field for smooth, thick and infinitely long structure which such surface rarely exists in reality, since the reflected field in the mobile path occurs from the buildings and streets which are rough and finite in size. Therefore, for better path loss prediction the first order reflection coefficient has to be modified especially in the area where the surface roughness is high. This problem has mentioned in Reference [7] where it was suggested that for a smooth surface the first order reflection coefficient can predict the reflected wave with reasonable accuracy, but for rough surface with finite width and thickness it was concluded that the first order reflection coefficient is inadequate and not good enough for field estimation.

Therefore, this paper considers reflection coefficient for indoor and outdoor wireless communication and concludes that for homogeneous medium with moderate roughness, the first-order reflection coefficient obtained from linear equation, is adequate. But for inhomogeneous medium the reflection coefficient is usually complex and can be expressed with nonlinear equation such as Riccati equation [8]. On the other hand, most of the nonlinear equations usually do not have analytic and exact solutions, so they have to be solved numerically with respect to different profiles. Therefore, for solving the Riccati equation the first step is to find the path profile and then approximating the nonlinear equation for that profile. The second step is to use the suitable numerical approach. However, it can be shown that when the reflection coefficient of the layer is weak, the Riccati differential equation can be solved iteratively [8].

The structure of this paper is as follows: in section II we outline the reasons for modifying the reflection coefficient and in section III the new reflection coefficients are introduced. In section IV the solution of the deterministic reflection coefficient in relation to the diffraction coefficient are provided. In section V the solution of the stochastic reflection coefficient in relation to the diffraction coefficient are provided. In section VI application of the modified reflection coefficient in diffraction coefficients and the new model for diffraction loss estimation are also presented. Finally, the theoretical results obtained for the reflection coefficient and diffraction loss are compared with the measurement data.

2. Reasons for modification of the reflection coefficient

In this section, we provide the reasons for justifying the reflection coefficient modification required for radio wave propagation. As mentioned above, for estimating the wave attenuation function caused by a building in wireless networks, different methods have been applied and most of these methods use reflection coefficient directly or indirectly in their procedure for path loss calculations. For example, the well known method for field estimation in the mobile network is ray tracing, GTD/UTD and Physical Optics based solution, where the accuracy of these methods relies on the reflection coefficient accuracy. That is, because ray tracing method is the asymptotic solution of Maxwell's equation and accordingly, the electric field received at the receiver is the sum of N rays (paths) that connect the source and the point of observation. These paths are: direct, reflected, diffracted, transmitted, reflected–diffracted, double–reflected, higher–order terms of reflection, diffraction rays and combination of them. Therefore, it is obvious that the reliability and accuracy of ray tracing methods depends heavily on the reflection coefficient used in the calculation procedure.

On the other hand, P.O. approach or Kirchhoff-Huygens methods not only have been applied in urban and rural areas for predicting multiple diffraction caused by obstacles in the path, but also they have been widely used as the deterministic methods for calculating the field scattered by the surfaces of the obstacles in the radio path. In fact the P.O. and ray tracing are also high frequency approximations of Maxwell's equation solution; these methods are extensively used for cell coverage calculations [5, 9-10].

The diffraction coefficient applied in ray tracing method for field calculations is defined as [2, 11]:

$$D_{s,h}(\phi,\phi',L,n,\beta_0) = D_1 + D_2 + \Gamma_{s,h}(D_3 + D_4) \qquad (1)$$

Where $\Gamma_{s,h}$ represents the first-order reflection coefficients (Fresnel reflection coefficient) of the surfaces of the wedge at the edge for soft and hard polarizations respectively.

Also D_1, D_2, D_3 and D_4 are defined as:

$$D_1 = \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k}\sin\beta_0}\cot\left(\frac{\pi+(\phi-\phi')}{2n}\right)F(kLa^+(\phi-\phi')) \qquad (2)$$

$$D_2 = \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k}\sin\beta_0}\cot\left(\frac{\pi-(\phi-\phi')}{2n}\right)F(kLa^-(\phi-\phi')) \qquad (3)$$

$$D_3 = \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k}\sin\beta_0}\cot\left(\frac{\pi+(\phi+\phi')}{2n}\right)F(kLa^+(\phi+\phi')) \qquad (4)$$

$$D_4 = \frac{-\exp(-j\pi/4)}{2n\sqrt{2\pi k}\sin\beta_0}\cot\left(\frac{\pi-(\phi+\phi')}{2n}\right)F(kLa^-(\phi+\phi')) \qquad (5)$$

Where the parameters k, β_0, a^+, a^-, L, ϕ, ϕ' and transition function F(x) are defined in [2]. As it can be seen later in the slope diffraction approximation, similar relation between diffraction coefficient and reflection coefficient exists [12].

On the other hand, in order to calculate the aperture fields using P.O. method we have:

$$J(\vec{r}') = \vec{n}\times\begin{bmatrix}1+\Gamma_s & 0\\ 0 & 1+\Gamma_h\end{bmatrix}\begin{bmatrix}H_s^i(\vec{r}')\\ H_h^i(\vec{r}')\end{bmatrix} \qquad (6)$$

$$M(\vec{r}') = -\vec{n}\times\begin{bmatrix}1+\Gamma_s & 0\\ 0 & 1+\Gamma_h\end{bmatrix}\begin{bmatrix}E_s^i(\vec{r}')\\ E_h^i(\vec{r}')\end{bmatrix} \qquad (7)$$

$$\vec{E}_s = \vec{E}_J + \vec{E}_M \qquad (8)$$

$$\vec{E}_J = \frac{jf\mu}{2}\frac{\exp(-j\beta r)}{r}\hat{r}\times\left(\hat{r}\times\int_s \vec{J}(\vec{r}')\exp(j\beta\,\hat{r}.\vec{r}')ds\right) \qquad (9)$$

$$\vec{E}_M = \frac{jf\mu\varepsilon}{2}\frac{\exp(-j\beta r)}{r}\hat{r}\times\int_s \vec{M}(\vec{r}')\exp(j\beta\,\hat{r}.\vec{r}')ds \qquad (10)$$

Again in these formulas $\Gamma_{s,h}$ represents the Fresnel surfaces reflection coefficients of the building's wall, $\hat{n}$ is the normal unit vector at the surface point $\vec{r}'$, $H^i_{s,h}(\vec{r}')$ and $E^i_{s,h}(\vec{r}')$ are the soft and hard components of the incident magnetic and electric field vectors at the surface point respectively, r is the distance between the center of the facet and the observation point $\vec{r}$ is a unit vector from the center of the facet to the observation point and S is the surface of the facet. As it can be clearly seen from these equations, the reflection coefficient plays an important role in field calculation and estimation in mobile path, using either P.O. or GTD/UTD methods. Therefore, more accurate reflection coefficient leads to better or more precise solution of the path loss estimation in mobile, radar and radio link calculations.

3. Reflection coefficient equations

The reflection coefficient of the reflecting wall or ground that is extended to infinity along y axis (in the x, y plane) can be modeled by Fresnel reflection coefficients, these coefficients are the first-order approximations of reflection coefficient [7]. For vertical and horizontal polarization the reflected fields can be obtained as:

$$\vec{E}_r = \overline{\Gamma}\vec{E}_i \qquad (11)$$

Where E_i, E_r are the incident and the received electric fields respectively and Γ is the first-order reflection coefficient. The relation between transmitted and received fields in terms of hard and soft (vertical and horizontal) reflection coefficients are given as:

$$\begin{bmatrix}E_s^r\\ E_h^r\end{bmatrix} = \begin{bmatrix}\Gamma_s & \cdot\\ \cdot & \Gamma_h\end{bmatrix}\begin{bmatrix}E_s^i\\ E_h^i\end{bmatrix} \qquad (12)$$

Where $\Gamma_{s,h}$ (first order approximation) are as follow:

$$\Gamma_h(\theta) = \frac{\varepsilon_r\cos(\theta) - \sqrt{\varepsilon_r - \sin^2(\theta)}}{\varepsilon_r\cos(\theta) + \sqrt{\varepsilon_r - \sin^2(\theta)}} \qquad (13)$$

$$\Gamma_s(\theta) = \frac{\cos(\theta) - \sqrt{\varepsilon_r - \sin^2(\theta)}}{\cos(\theta) + \sqrt{\varepsilon_r - \sin^2(\theta)}} \qquad (14)$$

Now if we consider a homogeneous layer with finite thickness (d) in this case the reflection coefficients can be modified as:

$$\Gamma_h(\theta_i) = (\varepsilon_r - \sin^2\theta_i - \varepsilon_r^2\cos^2\theta_i)\left[\exp(2jd\beta_0\sqrt{\varepsilon_r - \sin^2\theta_i}) - 1\right] / (\exp(2jd\beta_0\sqrt{\varepsilon_r - \sin^2\theta_i})(\sqrt{\varepsilon_r - \sin^2\theta_i} + \varepsilon_r\cos\theta_i)^2 - (\sqrt{\varepsilon_r - \sin^2\theta_i} - \varepsilon_r\cos\theta_i)^2) \qquad (15)$$

$$\Gamma_s(\theta_i) = (1-\varepsilon_r)\left[\exp(2jd\beta_0\sqrt{\varepsilon_r - \sin^2\theta_i}) - 1\right] /$$
$$(\exp(2jd\beta_0\sqrt{\varepsilon_r - \sin^2\theta_i})(\sqrt{\varepsilon_r - \sin^2\theta_i} + \cos\theta_i)^2 -$$
$$(\sqrt{\varepsilon_r - \sin^2\theta_i} - \cos\theta_i)^2) \tag{16}$$

with refer to Fig.1 d is the thickness of the reflection layer, θ is incident angle, β_0 is phase constant and ε_r is the complex relative dielectric constant of the layer which is given by:

$$\varepsilon_r = \frac{\varepsilon - j\frac{\sigma}{\omega}}{\varepsilon_0} \tag{17}$$

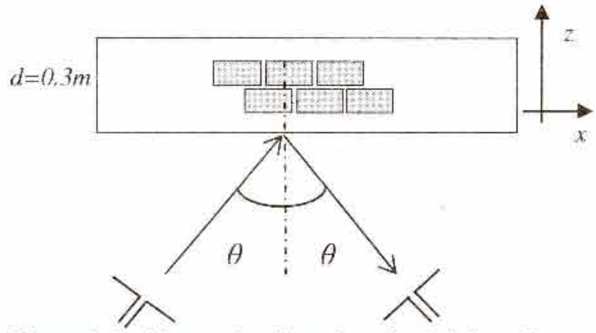

Figure 1 incident and reflected ray in a brick wall

Further for a moderate rough surface with Gaussian roughness having a height standard deviation $\sigma_h < \lambda$, (h stand for height of roughness) the reflection coefficient correction factor is defined as [2]:

$$\rho(x) = e^{-x}.I_0(x), \quad x = 8\left(\frac{\pi\sigma_h\cos(\theta)}{\lambda}\right)^2 \tag{18}$$

Where I_0 is the modified Bessel function of order zero, hence the new Fresnel reflection coefficients for rough surface can be represented as:

$$\Gamma_s(rough) = \Gamma_s.\rho \tag{19}$$

$$\Gamma_h(rough) = \Gamma_h.\rho \tag{20}$$

Finally, for a layer of inhomogeneous dielectric slab with dielectric constant change along z-axes (ε (z)) which is infinite along the x and y axes as shown in Fig.2. Also if we assume the incident wave to be plane wave with transverse electric polarization (TE), with an absorber, surface is located between the transmitter and receiver (the absorber surface absorb direct path between transmitter and receiver as shown in Fig.1). The reflection coefficients for this inhomogeneous slab can be represented as below.

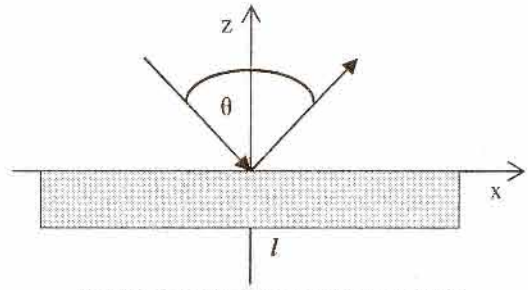

Figure 2 incident and reflected ray in inhomogeneous layer

If we consider a plane wave incident to this inhomogeneous layer, we have:

$$E^i = \hat{y}\exp(-jk_0x\sin(\theta) + jk_0z\cos(\theta)) \tag{21}$$

Where E^i is incident wave, k_0 is wave number and θ is incident angle respectively. Also from Maxwell's equations, we have:

$$\frac{\partial E_y}{\partial z} = j\omega\mu H_x \tag{22}$$

$$\frac{\partial E_y}{\partial x} = j\omega\mu H_z \tag{23}$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = j\omega\varepsilon E_y \tag{24}$$

Now for calculating the reflection coefficient of this inhomogeneous layer we represent the incident and reflected fields at any point in the layer as:

$$E_y^i = A(z) \quad E_y^r = B(z) \tag{25}$$

if the new reflection coefficient, R, is defined as:

$$R = \frac{B(z)}{A(z)} \tag{26}$$

where R can be obtained from the solution of the nonlinear differential equation known as the Riccati equations which have the general form:

$$R' = -j2k_zR + \frac{k_z'}{2k_z}(1-R^2) \tag{27}$$

in this formula R' is derivative of R with respect to z and can be written as:

$$R' = -j2k_zR + \gamma(1-R^2) \tag{28}$$

also γ for TE and TM mode are given as:

$$\gamma = \begin{cases} \dfrac{k_z'}{2k_z}, & TE \\ \dfrac{1}{2}\left(\dfrac{k_z}{\varepsilon_r}\right)\dfrac{\varepsilon_r}{k_z}, & TM \end{cases} \tag{29}$$

Furthermore, for wave impedance similar Riccati equation exists and is given by:

$$\eta' = jk_0\left[1-\left(\frac{k_z}{k_0}\right)^2\eta^2\right] \tag{30}$$

Where η is normalized impedance:

$$\eta = Z/Z_0 \tag{31}$$

by changing the variable one can obtain simpler Riccati equation as [8]:

$$\xi = \eta/jk_0 = Z/jk_0Z_0 \tag{32}$$

$$\xi' = 1 + k_z^2\xi^2 \tag{33}$$

After solving either of these Equations (28 or 33) the same answers for reflection coefficients are obtained.

For solving these nonlinear equations we need to determine boundary conditions. The boundary condition in these problems is obtained by assuming that the reflection coefficient at the lowest layer is zero (since the medium characteristics gradient does not exist at that point).

4. Solution of the nonlinear Riccatti equations

For solving nonlinear equations such as the Riccati equation various numerical methods such as method of moment, finite element, finite difference method (FDM), and finite difference time domain can be applied. In this paper FDM has been applied.

As we know in FDM the stability is an important requirement; therefore in order to find which value of Δz leads to the stable condition, the Riccati equation must be solved and checked for convergence with various values of Δz. This is necessary since for nonlinear equations stability condition does not obey a linear and distinguished pattern. Therefore for solving Riccati equation with stable condition, first we discretize Riccati equations (Equation (28)) in terms of wall thickness:

$$R_{n+1} = -j12\pi R_n\Delta z\sqrt{\varepsilon_r(1-n\Delta z)-\sin^2\theta_0} + \frac{\varepsilon_r'(1-n\Delta z)}{4\left(\varepsilon_r(1-n\Delta z)-\sin^2\theta_0\right)}(1-R_n^2)\Delta z + R_n \tag{34}$$

$$R_{n+1} = -j12\pi R_n\Delta z\sqrt{\varepsilon_r(1-n\Delta z)-\sin^2\theta_0} + \left[\frac{\varepsilon_r'(1-n\Delta z)}{4\left(\varepsilon_r(1-n\Delta z)-\sin^2\theta_0\right)} - \frac{\varepsilon_r'(1-n\Delta z)}{2\varepsilon_r(1-n\Delta z)}\right](1-R_n^2)\Delta z + R_n \tag{35}$$

Where in the above equations n varies from 0 to 100 which corresponds to z = 1m and Δz = 0.01 (z is the wall thickness). After substituting different value of Δz in Eq. (34) and (35) we observed that the stable condition occur if $\Delta z \leq$ 0.01m.

Having found stable condition, the discredited reflection coefficient at any point in the wall can be obtained using above formulas if the dielectric constant of the wall at different point is known. Since it can be seen that Eq. (34) and (35) depend on the electrical properties of the wall or more generally on the profile of the surface, therefore for this purpose we assume that the walls' surface have dielectric constant profile as shown in Figs. 3 and 4. (In Fig. 3 we assume that the wall consists of one layer and in Fig. 4 two layers of inhomogeneous bricks).

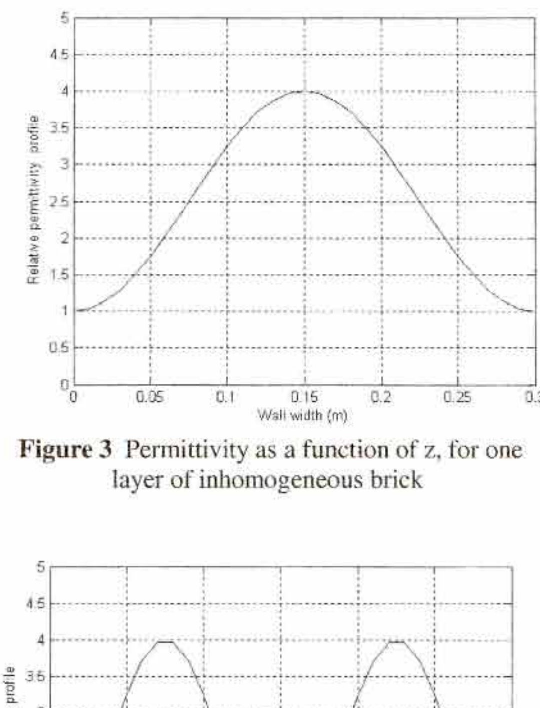

Figure 3 Permittivity as a function of z, for one layer of inhomogeneous brick

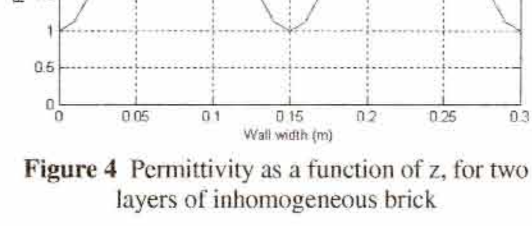

Figure 4 Permittivity as a function of z, for two layers of inhomogeneous brick

With the above assumption and profiles 3 and 4 the nonlinear Riccati equation is solved with FDM for TE and TM modes in this paper. The calculated and measured results for magnitude and phase of the reflection coefficient are shown in Figs. 5, 6, 7, 8, 9, 10, for TE and TM modes. Also in these figures for comparison, the phase and magnitude of the first reflection coefficient are plotted.

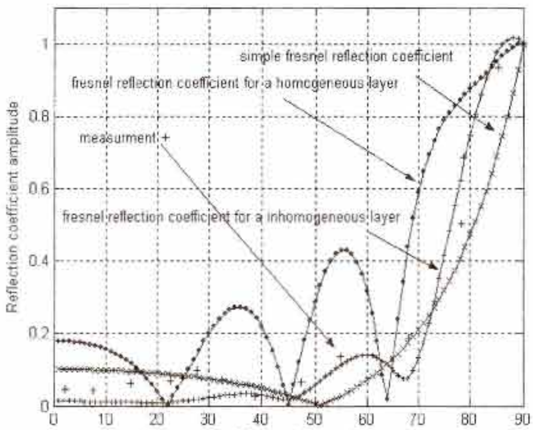

Figure 5 Magnitude of reflection coefficient in accordance to incident angle for TE mode and profile shown in figure 3

It is clear from these figures that the results obtained from the modified reflection coefficient (Riccati equation) are more close to measurement results when compared with either the first order or modified first order reflection coefficient.

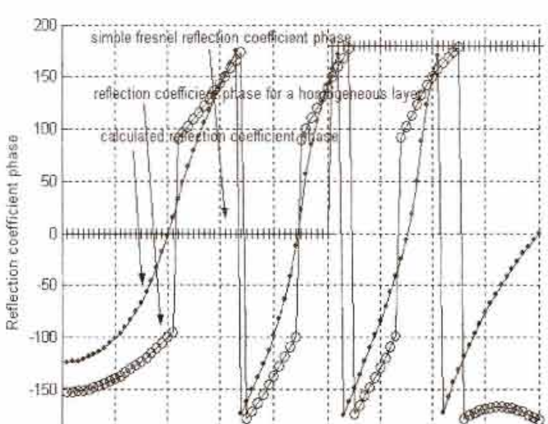

Figure 6 Phase of reflection coefficient in accordance to incident angle for TE mode and profile shown in figure 3

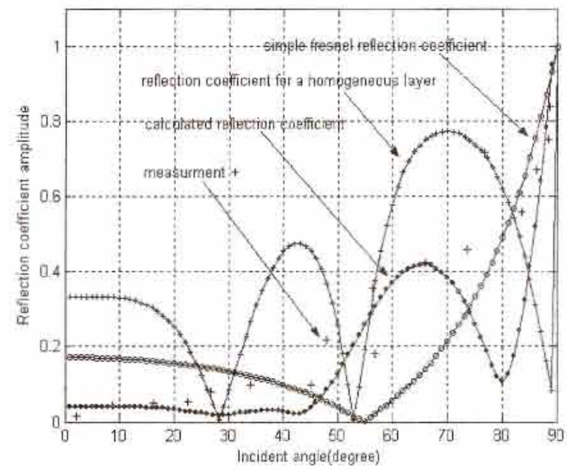

Figure 7 Magnitude of reflection coefficient in accordance to incident angle for TE mode and profile shown in figure 4

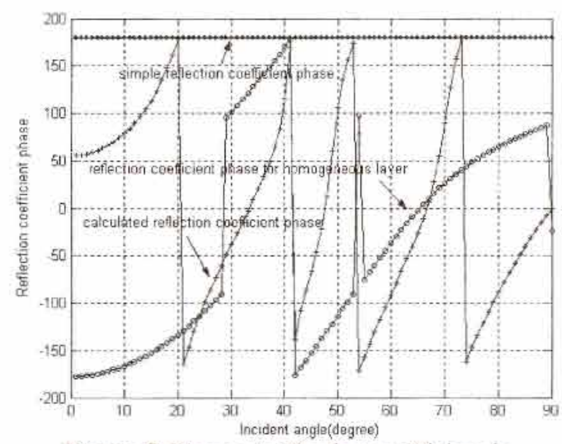

Figure 8 Phase of reflection coefficient in accordance to incident angle for TE mode and profile shown in figure 4

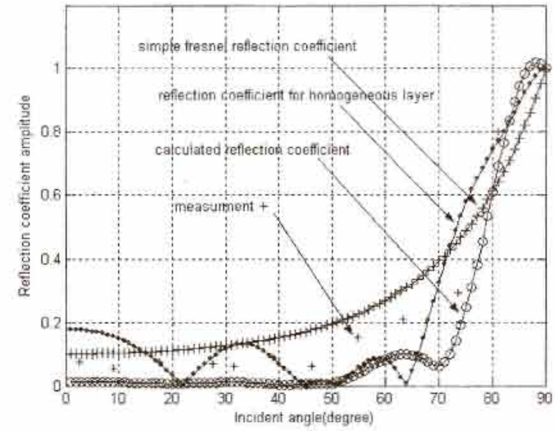

Figure 9 Amplitude of Reflection coefficient for TM mode and profile shown in figure 3

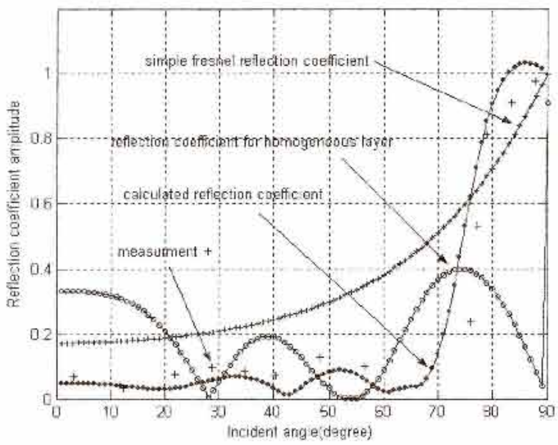

Figure 10 Amplitude of reflection coefficient in accordance to incident angle for TM mode and profile shown in figure 4

Furthermore, from these figures we conclude that the phase obtained using Riccati nonlinear equation are approximately the same as the phase of the reflection coefficient for homogeneous layer given by equations 15 and 16 but it differ from the phase obtained from Eq.s 13 and 14. Therefore, as the phase reflection coefficient is an important parameter in multipath delay calculation, the modified reflection coefficient introduced in this paper can estimate the phase and magnitude of the reflection coefficient- as well as the reflected and diffracted field- for different walls with any degree of roughness with better accuracy compared with previous methods.

Also for TM mode and profiles given in figures 3 and 4 the calculated and the measured results are shown in figures 9 and 10.

5. Reflection coefficient calculation for surface with stochastic roughness

The deterministic reflection coefficient considered up to now cannot encompass all scenarios. For this reason we assume the true reflection coefficient is a white random process with a mean function. The deterministic Riccati equation is now invoked by a stochastic reflection coefficient. The new formulation is a deterministic Riccati equation with a random input. The solution we seek to obtain is the mean and the variance; the variation, around this mean. Mean solution of the Riccati equation on the other hand will provide the average propagation behavior for all buildings. The variation around the mean with respect to angle of incidence provides how sensitive the propagation is with respect to this angle. A foresight into the behavior of the propagation with respect to reflection coefficient is the variance of the white random process. This variance can serve as a measure of uncertainty in our modeling strategy. It is shown numerically that the solution of the Riccati equation is not a strong function of this parameter when the angle of incidence is held constant. The more the variance of the white process, the more deviation exists beyond the deterministic input. However, we reach an unrealistic reflection coefficient for very large variances of the additive white random process as in Fig. 12.

Fig. 11 shows the reflection coefficient for rough surface. The roughness of surface is assumed to be normal probability density function with standard deviation and mean are equal to 0.1 and 0, respectively. Figure 12 presents the magnitude of the reflection coefficient against the standard deviation of the relative permittivity for profile shown in Fig. 4 and TE mode when the incident angle equals 60°.

6. Application of the modified reflection coefficient in diffraction coefficient estimation

As mentioned in [13], the diffraction coefficient is given by:

$$D_{s,h}(\varphi,\varphi',L,n,\beta_0)= D_1 + \Gamma_{s,h,0}\,\Gamma_{s,h,n}\,D_2+\Gamma_{s,h,0}\,D_3+\Gamma_{s,h,n}\,D_4 \qquad (36)$$

where D_1, D_2 , D_3 , D_4 are defined in equations (2)-(5) and $\Gamma_{s,h,0}$, $\Gamma_{s,h,0}$ are reflection coefficients of the face 0 and n of a wedge respectively. As it can be seen from Eq. (36) the diffraction coefficient depends on reflection coefficient, therefore after applying the modified reflection coefficients to the above formula, the diffracted fields are calculated as shown in Fig. 13. In this calculation the incident field assumed to be plane wave and the interior wedge angle 90 degree.

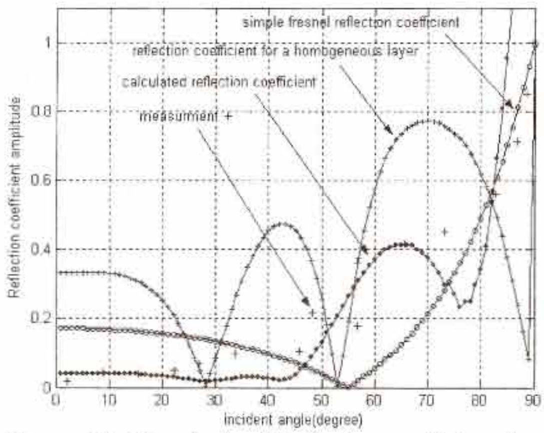

Figure 11 Magnitude of Reflection coefficient for TE mode and profile shown in figure 3 when roughness of surface is taken into account.

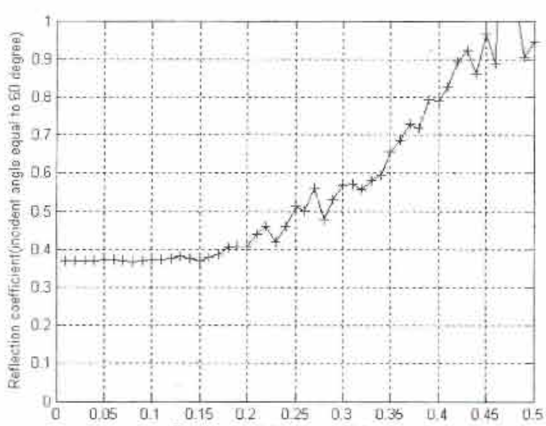

Figure 12 Magnitude of reflection coefficient in accordance to standard deviation of relative permittivity for TE mode and profile shown in figure 3 with incident angle equal to 60°

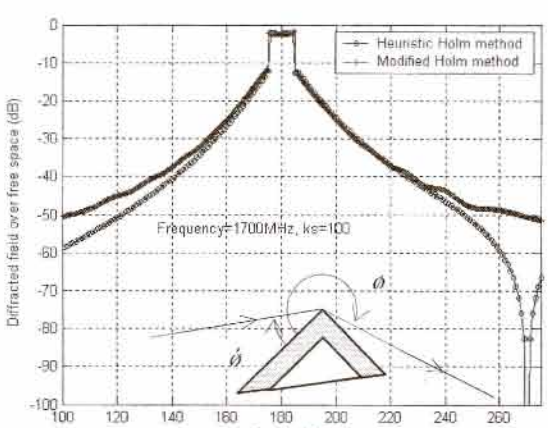

Figure 13 Diffracted field vs incident angle (plane wave), n=3/2, ϕ́=5°, ε_r=8 and σ=0.001 S/m.

Also in Fig. 13, the diffracted field is calculated using Holm diffraction coefficients. As it can be seen from this figure the Holm diffraction coefficient [13] has a deep null when the incident angle is around 275 degree which corresponds to a zero diffracted field or shadow region. This null does not appear when using diffraction coefficient with the modified reflection coefficient. As it is well known, this situation does not happen in practice since the received field has a smooth behavior in the shadow regions. Therefore, the diffraction field calculated using the modified reflection coefficient can estimate the diffracted fields more closely than the diffraction coefficient using the first order reflection coefficient. This is because the modified reflection coefficient can estimate the phase of the received reflected field with more accuracy than then Fresnel reflection coefficient.

Also in mobile communications the path usually consists of a row of buildings, therefore it is interesting to calculate the excess path loss due to row of buildings using the modified reflection and diffraction coefficient. For this propose we assume n rows of buildings with space width "d" as shown in Fig. 14, then the total electric field, at the nth building can be written as:

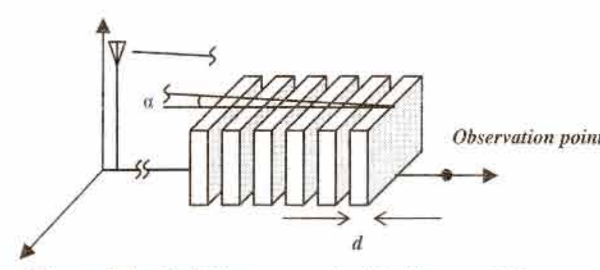

Figure 14 n buildings spaced with distance "d".

$$\vec{E}_{tot}(n+1) = E_0\left[e^{-jknd\cos\alpha} + \left\{ \frac{D_\alpha}{\sqrt{d}} e^{-jkd(1+(n-1)\cos\alpha)} \times \frac{1-(D_{\pi/2} e^{jkd(\cos\alpha-1)}/\sqrt{d})^n}{1-D_{\pi/2} e^{jkd(\cos\alpha-1)}/\sqrt{d}} \right\}\right] \qquad (37)$$

where $D_{s,h}$ (α) and $D_{s,h}$ (π/2) can be calculated from equations 2-5 as follows [14]:

$$D_{s,h}(\alpha) = D_{s,h}\,(L = d\ ,\ \phi = 3\pi/2\ ,\ \acute{\phi} = \pi/2 + \alpha\ ,\ \beta' = \pi/2) \qquad (38)$$

$$D_{s,h}\,(\pi/2) = D_{s,h}\,(L = d/2\ ,\ \phi = 3\pi/2\ ,\ \acute{\phi} = \pi/2\ ,\ \beta' = \pi/2) \qquad (39)$$

Furthermore, with reference to Fig. 15, Eq. (37) can be modified by taking into account the reflected path from ground. Therefore for this new situation the corresponding equations are modified as follows:

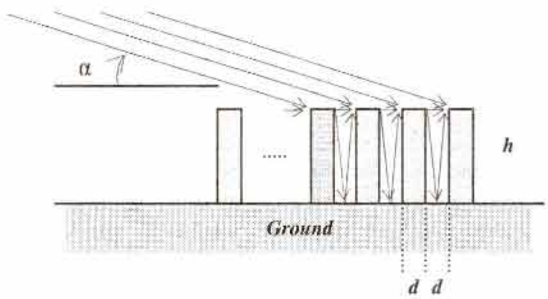

Figure 15 n row of buildings spaced with distance "d"and height "h"

$$\vec{E}_{tot}(n+1) = E_0\left[e^{-jknd\cos\alpha} + \left\{ \frac{D_\alpha}{\sqrt{d}} e^{-jkd(1+(n-1)\cos\alpha)} \times \frac{1-(D_{\pi/2}e^{jkd(\cos\alpha-1)}/\sqrt{d})^n}{1-D_{\pi/2}e^{jkd(\cos\alpha-1)}/\sqrt{d}} \right\}\right] + E_0\left[R \quad e^{-jkn2\sqrt{h^2-d^2/4}}/\sqrt{h^2+d^2/4}\left\{ \frac{D_\alpha}{\sqrt{d}} e^{-jkd(1+(n-2)\cos\alpha)} \times \frac{1-(D_{\pi/2}e^{jkd(\cos\alpha-1)}/\sqrt{d})^{n-1}}{1-D_{\pi/2}e^{jkd(\cos\alpha-1)}/\sqrt{d}} \right\}\right] \tag{40}$$

In Eq. (40) R is the reflection coefficient from ground which can be obtained from Eq. (28).

Finally it can be argued that the higher order diffraction term can play an important role in the diffraction mechanism and ignoring them usually leads to errors in field estimation, especially in the multiple wedge cases (which normally occurs in mobile communication, radar, radio wave propagation and NDT). Therefore, in order to consider the higher order diffraction coefficients for two wedges, the received field is modified by using the new reflection coefficient as well as the higher order term diffraction coefficient as shown below [15]:

$$\vec{E}_{UTD} = E_0 \frac{e^{-jks_T}}{s_T}\sqrt{\frac{s_T}{s_1 s_2 s_3}}\sum_{m=0}^{\infty}\frac{1}{m!}\left(\frac{-1}{jks_2}\right)^m \cdot \frac{\partial^m D_1}{\partial\phi_1'^m}\frac{\partial^m D_2}{\partial\phi_2'^m} \tag{41}$$

In this formula S_T, S_1, S_2 and S_3 are defined in [13].

The first order diffracted field is obtained by putting, m = 0 in Eq. (41). The received field $\vec{E}_{UTD}$ in this paper is also calculated using Eq. (41) by ignoring the diffraction coefficient higher than 5 since it was observed that the higher terms (>5) do not change the result more than 1%, so they can be ignored without losing accuracy.

The calculated results using Equation (41) for configuration 14 and 15 with higher order (5th order) diffraction coefficients (using modified reflection coefficient) are shown in Fig. 18.

It can be seen from Fig. 18 that the settling behavior occurs for the electric field when n > 5 (number of building) therefore it is accurate enough to calculate the electric or excess path loss when the number of building are greater or equal to 5.

In this paper with the above assumptions, the excess power loss for multiple diffraction from buildings is calculated using both the first-order and modified reflection coefficient (diffraction coefficient with modified reflection coefficient and also taking into account the higher-order term for diffraction coefficient as given by Eq. (41)).

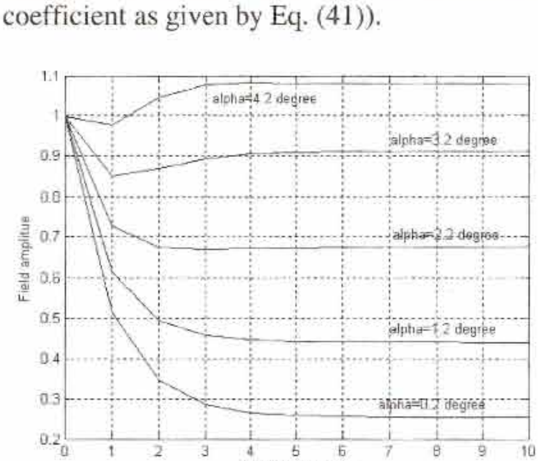

Figure 16 Field amplitude vs. building number for multiple diffraction from roof of buildings

The results are plotted in Fig. 19, also in this figure the measurement obtained from reference [15] for a row of buildings is shown. As it can be seen from Fig. 19 the proposed model agrees more closely with the measurement data. This justifies our argument about the need for modification of the reflection coefficient as well as taking into account higher-order terms for diffraction coefficient, if better field estimation in mobile communications is required.

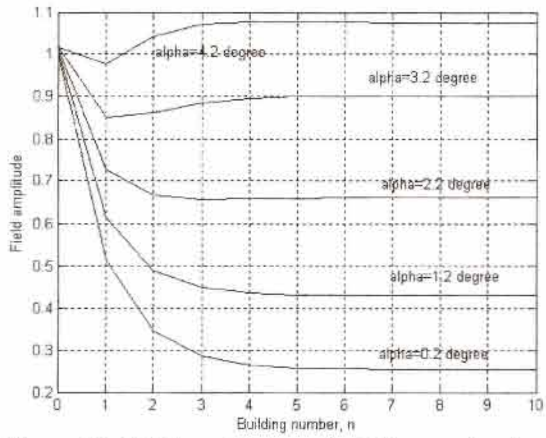

Figure 17 Field amplitude vs. building number for multiple diffraction from roof of buildings and taking into account reflection from the ground

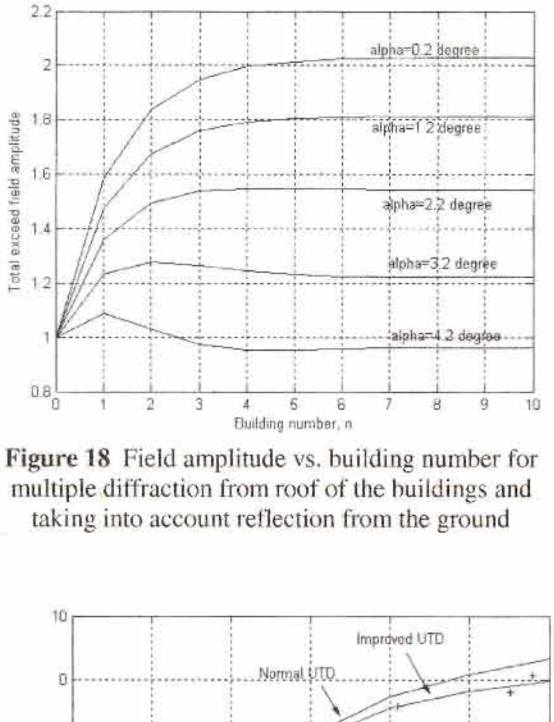

Figure 18 Field amplitude vs. building number for multiple diffraction from roof of the buildings and taking into account reflection from the ground

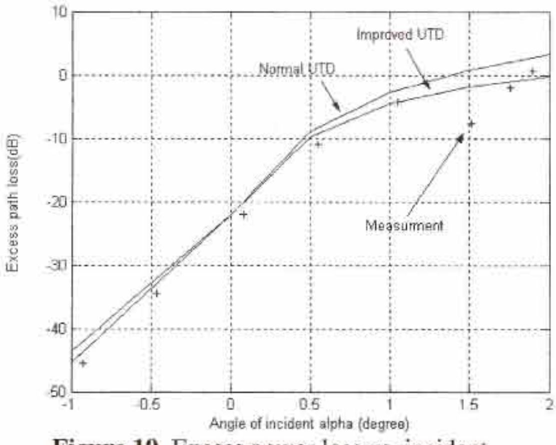

Figure 19 Excess power loss vs. incident angle to building

7. Conclusions

In this paper, we have shown that the normal reflection coefficient that is usually used in the past for path loss estimation is not accurate enough for calculating the reflected and diffracted fields in mobile communications. We introduced a modified reflection coefficient that originates from the Riccati nonlinear equation for this purpose. By applying the modified reflection and diffraction coefficients to a row of buildings with inhomogeneous profile, the excess path loss as well as the diffraction loss was calculated. It was observed that the results obtained from this model agree more closely with the measurement data, this is so since the new reflection coefficient relies on the nonlinear equation and exact profile of the media. Therefore, any profile (deterministic or stochastic) for walls can be implemented and reflection and diffraction coefficient can be estimated for them. Also in this paper the path losses are calculated by using the new reflection coefficient as well as higher-order diffraction coefficient for a row of buildings. The results obtained in this paper for phase and magnitude of the reflection coefficient as well as for diffraction loss are in close agreement with the measurement data obtained elsewhere. Therefore, it can be concluded that by using the modified reflection coefficient and adding higher-order terms for the diffraction coefficient, the path loss can be estimated more accurately.

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