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IMPACT OF A CONCRETE ROOM ON THE PERFORMANCE OF CELLULAR TELEPHONE COMMUNICATIONS FOR LOW BIT RATE APPLICATIONS

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ABSTRACT

In this paper, a new propagation model, in macrocellular wireless communication systems, is derived. The model characterizes the base station to mobile radio channel when the propagated signal is being obstructed by lossy concrete room in which the mobile phone moves. The analysis is performed by using ray-tracing techniques combined with uniform theory of diffraction (UTD), in addition to using a UTD modified heuristic diffraction coefficient for non-perfectly conducting wedges. The maximum considered ray reflections are three, single and double diffractions are also considered in this study. Therefore, all expected significant ray contributions in multipath channel are included. These rays include direct, reflected, refracted and diffracted paths, or any combination of the mentioned paths. The mathematical propagation model is derived, after which the model is implemented by different computer programs written in Matlab. For low bit rate applications (narrowband systems), the attenuation and fading of the propagated signal are the main causes of signal degradation. Therefore, the signal strength, as a function of mobile location inside the room, was computed for base station with an antenna array. The depolarization effect on propagated signal as well as the cumulative distribution function (CDF) and probability density function (PDF), that are useful for statistical prediction models, are studied. Details of the present model that may facilitate implementation are given. Comparison with measurements revealed acceptable agreement. The results of this research work should be useful in radio link design of macrocellular land mobile communication systems.

Keywords: model, cellular phone, propagation, base station, diffraction, ray tracing, concrete room, measurements.

1. INTRODUCTION

There is a strong correlation between the distance of a base station and its signal strength, so different research works focused on received signal strength measurements [1-2]. Paper [3] is a survey of many propagation prediction methods, which provide an initial estimation of the signal characteristics for mobile communication, such as the ray tracing methods which can deterministic propagation predictions. provide Α deterministic ray tracing wave propagation model was compared to wide-band channel measurements at 2 GHz and 5.2 GHz carried out in the city of Karlsruhe in Germany [4]. There are numerous papers in which the use of ray tracing propagation through building walls was discussed [6, 7]. These papers studied the ray transmitted through buildings based on propagation prediction model; the propagated rays are traced from outdoor to indoor through building walls. When the radio waves are being transmitted through the buildings, the penetration loss causes the signal to be severely attenuated, especially if the receiver is mobile. The most important factors influencing building penetration loss have been discussed, namely, angle of incidence, external wall configuration, and receiver height [8]. For the calculation of the ray contributions in deterministic methods, a combination of geometrical optics (GO) and uniform theory of diffraction (UTD) was applied [9]. An expression for the diffracted electric field is derived in closed form and given in terms of the UTD transition function, where the diffraction contributions are evaluated by means of uniform asymptotic physical optics solution [5]. This diffraction model of lossy wedge is intended for predicting the

electric field in microcellular environments. Finally, the polarization of received signal emitted by a portable transmitter from outdoor and indoor paths was measured in cellular mobile communications environments [10].

In this paper, the received signal at mobile terminal is predicted by using uniform theory of diffraction (UTD) with ray optics to model the radio wave propagation in a macro-cell. The high-frequency techniques including the UTD are usually used when the wavelength of the incident or radiated wave is small compared to structures with which it interacts. However, good results are obtained when the smallest dimension of a large structure is greater than $2\lambda/3 = 0.67\lambda$ [7]. In the present work, the usual room dimensions are: length 4 m, height 3 m, and wall thickness 0.27 m, and door height 2.1 m. Thus, the smallest dimension is the wall thickness of 0.27 m which amounts to 0.81λ at the mobile frequency of 900 MHz, and 1.62\lambda at 1800 MHz. Furthermore, we found that for typical distances of base station from the room, e.g., 150 m, the total contribution of rays reflected from or penetrated through the wall end (Figures 6 and 8) is 15 dB below the total received field strength. So, the usual dimensions of a room are valid to be analyzed by the GTD (or its improved version UTD). It is worth mentioning here that solving this problem using full-wave numerical methods such as the finite element method would require an extremely large number of unknowns due to the large dimensions of a room (in addition to the absorbing boundary distances) compared with wave length at the cellular frequencies of 900 MHz or 1800 MHz. A mathematical model is introduced by deriving equations to calculate the received signal due to each path which



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reaches the mobile phone from base station antenna, and predicting the signal strength at mobile by adding the received signals of each path. Horizontal, vertical, and circular polarizations of the radio wave are considered. The model takes into account all significant multi path signals that originate from base station to mobile inside building including direct, reflected, refracted and diffracted paths, or any combination of the mentioned paths. In narrowband low bit rate systems, the propagation attenuation and fading statistics are the main causes of signal degradation. Therefore, narrowband performance is checked by computing the signal level versus mobile location inside the room. For circularly polarized transmitted signals, polarization degradation is evaluated by computing the value of the axial ratio as a function of mobile distance. This research sheds light on downlink communication in one macro cell system type; taking into consideration the impact of room or rooftop on communication performance.

2. SUGGESTED MACRO CELL PROPAGATION MODEL

The geometry of the propagation model is illustrated in Figure-1. A base station antenna of height h_{bs} radiates a spherical wave that can be represented as rays that can reach a mobile terminal inside a room of height h_b and width w_b, where the mobile antenna is located at a height h_m above the ground. Ray paths are calculated by determining the location of an image source for each reflecting surface; multiple reflections use images of the mobile images [16]. There are often several paths involving multiple reflections from the sidewalls of the room, from the ground, and from the ceiling, hence a ray can undergo many reflections before its field strength is reduced to an insignificant value. We found, by calculations for various typical scenarios, that three multiple reflections from the surfaces inside the room are adequate. Any ray that reaches one of the 11 points shown in Figure-1 will reach the mobile antenna if it is incident on the building or on its image. These points represent the mobile images through ground, walls and ceiling of the building, the points is interpreted in Table-1; it simulates all ray paths except diffracted rays. Table-1 gives x and y coordinates for each point. If the ray suffered from penetration through wall or ceiling, the ray path will be shifted a little horizontal or vertical distance; this shift is also calculated. Moreover, single and double diffractions

from the end wall structure edges of the building (from points A and B in Figure-1) are calculated. The ray diffracted paths are computed in combination with a maximum of two reflections. As the uniform theory of diffraction (UTD) [11] considers diffraction from only perfectly conducting wedges, we used a UTD modified heuristic diffraction coefficient for non-perfectly conducting wedges [12] in order to compute the diffraction coefficients of the points A and B shown in Figure-1. The frequency of transmitted signal from base station to the mobile is 900 MHz. At this frequency, the building is assumed to be lossy dielectric. The mobile phone height is 1.5 m. The inner dimensions of the room are: inner length is 4 m, inner height 2.8 m, door height 2.1 m, and wall thickness 0.27 m. Base station antenna height is 30 m. The values of conductivity σ are 0.005 S/m, 0.092 S/m for ground and concrete room, respectively, whereas the relative permittivity ε_r is 15, 5.5 for ground and concrete room, respectively, [17], at frequency of 900 MHz. These values are used in the calculation of reflection and transmission coefficients. However, the algorithm can be applied for other dimensions, parameters, and frequencies provided that the base station height is greater than the building height.



Figure-1. Propagation model: base station antenna radiating towards a mobile phone inside concrete room. The 11 points are the mobile phone images through reflecting surfaces.



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Image number	Image location	X coordinate	Y coordinate
1	mobile phone location	$x_{bs} + t + x_{m1}$	$h_{bs} - h_m$
2	ground image of 1	$x_{bs} + t + x_{m1}$	$h_{bs} + h_m$
3	right wall image of 1	$x_{bs} + t + x_{ms} + 2x_{ms}$	$h_{bs} - h_m$
4	right wall image of left wall image of 1	$x_{bs} + t + 2(x_{m1} + x_{m2}) + x_{m1}$	$h_{DS} - h_m$
5	ground image of ceiling image of 1	$x_{bs} + t + x_{m1}$	$\boldsymbol{h}_{bs} - \boldsymbol{h}_m + 2(\boldsymbol{h}_b - \boldsymbol{t})$
6	ground image of 3 or wall image of 2	$x_{bs} + t + x_{ms} + 2x_{ms}$	$h_{DS} + h_m$
7	left wall image of right wall image of 3	$x_{bs} + t + 3(x_{m1} + x_{m2}) + x_{m2}$	$h_{DS} - h_m$
8	wall image of 5	$x_{bs} + t + x_{ms} + 2x_{ms}$	$\boldsymbol{h}_{bs} - \boldsymbol{h}_m + 2(\boldsymbol{h}_b - \boldsymbol{t})$
9	ground image of ceiling image of 2	$x_{bs} + t + x_{mi}$	$h_{bs} + h_m + 2(h_b - t)$
10	ground image of wall end image of 1	$x_{bs} + t + x_{m1}$	$h_{bs} - h_m + 2h_g$
11	ground image of wall end image of 2	$x_{bs} + t + x_{m1}$	$h_{bs} + h_m + 2h_g$

Table-1. Mobile images' coordinates, note that coordinates center is at transmitting antenna.

3. FORMULATION OF RAY CONTRIBUTIONS

In all the equations below, for soft (horizontal) polarization, the signal that reaches the mobile phone is given in terms of the incident electric field at mobile denoted by E^{in} (mobile), while for hard (vertical) polarization, the signal is given in terms of magnetic field Hⁱn (mobile). The path length from base station antenna to the mobile terminal is called r_n . The number n indicates the path number identified in Table-2, this table includes the 70 different ray paths derived to implement this model.

The rays reach the mobile antenna by different paths with different angles. It may be firstly incident on the ceiling or the wall of the building or may enter from opened door, so we can divide these ray contributions of the received signal into 8 cases according to angle of ray that is incident on the building (the elevation angle). Hence, in each case, the ray has its own circumstances and mathematical model that is different from the other cases. In cases 1 to 7 the elevation angle has ranges as shown in Figure-2. The elevation range of case 1 is $\Theta_1 < \Theta < \Theta_2$, the range of case 2 is $\Theta_2 < \Theta < \Theta_2$, the range of case 3 is $\Theta_2 < \Theta < \Theta_4$, the range of case 4 is $\Theta_4 < \Theta < \Theta_5$, the range of case 5 is $\Theta_5 < \Theta < \Theta_6$, the range of case 6 is $\Theta_6 < \Theta < \Theta_7$, and the range of case 7 is $\Theta_7 < \Theta < \Theta_8$. The expressions for these elevation angles are:

$$\begin{split} \Theta_{1} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b}}{\mathbf{x}_{bs} + \mathbf{w}_{b} - \mathbf{t}} \right), \\ \Theta_{2} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b}}{\mathbf{x}_{bs} + \mathbf{t}} \right), \\ \Theta_{3} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b}}{\mathbf{x}_{bs}} \right), \\ \Theta_{4} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} + \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{5} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{g}}{\mathbf{x}_{bs}} \right), \\ \Theta_{6} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} + \mathbf{h}_{g}}{\mathbf{x}_{bs} + \mathbf{t}} \right), \\ \Theta_{7} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} + \mathbf{h}_{g}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &< \tan^{-1} \left(\frac{\mathbf{h}_{bs} + \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} + \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{bs} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{bs}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{b}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{b}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{b}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{b}} \right), \\ \Theta_{8} &= \tan^{-1} \left(\frac{\mathbf{h}_{b} - \mathbf{t}}{\mathbf{x}_{b}} \right), \\ \Theta_{8} &$$

The contributions of ray diffractions from room edges are presented in case 8. In cases 1 to 7, three reflections are included, but in case 8 two reflections in addition to single diffraction, or one reflection in addition to double diffractions, are included.

Table-2.	The eight	cases of ray	path contribu	ations receive	d by the mobile

Case number	Case title	Path number	Path title
Case-1	Ceiling	Path1	Ceiling penetration
	penetration	Path2	Ceiling penetration followed by ground reflection
		Path3	Ceiling penetration followed by wall reflection
		Path4	Ceiling penetration followed by two wall reflections
		Path5	Ceiling penetration followed by ground then ceiling reflections
		Path6	Ceiling penetration followed by either (wall then ground reflections) or
			(ground then wall reflections) or (corner between ground and wall
			reflection)
		Path7	Ceiling penetration followed by three wall reflections



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		Path8	Ceiling penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)
		Path9	Ceiling penetration followed by ground then ceiling then ground reflections
		Path1	Ceiling-wall penetration
		Path2	Ceiling-wall penetration followed by ground reflection
		Path3	Ceiling-wall penetration followed by wall reflection
		Path4	Ceiling-wall penetration followed by two wall reflections
		Path5	Ceiling-wall penetration followed by ground then ceiling reflections
		Path6	Ceiling-wall penetration followed by either (wall then ground reflections)
Case-2	Ceiling-wall		or (ground then wall reflections) or (corner between ground and wall reflection)
Cuse 2	penetration	Path7	Ceiling-wall penetration followed by three wall reflections
		Path8	Ceiling-wall penetration followed by either (ground then wall then
		i unio	ceiling reflections) or (from ground then ceiling then wall then
			reflections) or (wall then ground then ceiling reflections) or (corner
			between ground and wall reflection then ceiling reflection)
		Path9	Ceiling-wall penetration followed by ground then ceiling then ground
			reflections
		Path1	Wall-ceiling penetration
		Path2	Wall-ceiling penetration followed by ground reflection
		Path3	Wall-ceiling penetration followed by wall reflection
		Path4	Wall coiling penetration followed by two wall reflections
		Path6	Wall-ceiling penetration followed by ground then ceiling reflections
		1 auto	or (ground then wall reflections) or (corner between ground and wall
Case-3	Wall-ceiling		reflection)
	penetration	Path7	Wall-ceiling penetration followed by three wall reflections
		1 will /	
		Path8	Wall-ceiling penetration Ceiling-wall penetration followed by either
		Path8	Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling
		Path8	Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections)
		Path8	Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)
		Path9	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceilingthen wall then reflections) or (wall then ground then ceiling reflections)or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then groundreflections
Case-4		Path8 Path9 Path1	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall-ceiling penetration followed by ground then ceiling then ground reflections
Case-4		Path8 Path9 Path1 Path2	Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetrationWall penetration followed by ground reflection
Case-4		Path9 Path1 Path2 Path3	Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by ground reflectionWall penetration followed by ground reflection
Case-4		Path8 Path9 Path1 Path2 Path3 Path4	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by wall reflectionWall penetration followed by wall reflectionWall penetration followed by wall reflectionWall penetration followed by two wall reflections
Case-4		Path9 Path1 Path2 Path3 Path4 Path5	Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling then ground reflections Wall penetration Wall penetration followed by ground reflection Wall penetration followed by wall reflection Wall penetration followed by two wall reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by wow all reflections Wall penetration followed by two wall reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by ground then ceiling reflections
Case-4	A Wall	Path9 Path1 Path2 Path2 Path3 Path4 Path5 Path6	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by ground reflectionWall penetration followed by wall reflectionWall penetration followed by wall reflectionsWall penetration followed by two wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by either (wall then ground reflections) or(ground then wall reflections) or (ground then wall reflections) or
Case-4	A. Wall	Path8 Path9 Path1 Path2 Path3 Path4 Path5 Path6	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by wall reflectionWall penetration followed by two wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by two wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by or (corner between ground and wall reflection)
Case-4	A. Wall penetration	Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by wall reflectionWall penetration followed by two wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by two wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by either (wall then ground reflections) or (ground then wall reflections) or (corner between ground and wall reflection)Wall penetration followed by three wall reflections
Case-4	A. Wall penetration	Path9 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by wall reflectionWall penetration followed by wall reflectionsWall penetration followed by two wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by either (wall then ground reflections) or (ground then wall reflections) or (corner between ground and wall reflection)Wall penetration followed by three wall reflectionsWall penetration followed by three wall reflections
Case-4	A. Wall penetration	Path9 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8	Wall-ceiling penetration Ceiling-wall penetration followed by either(ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)Wall-ceiling penetration followed by ground then ceiling then ground reflectionsWall penetrationWall penetration followed by ground reflectionWall penetration followed by ground reflectionWall penetration followed by wall reflectionsWall penetration followed by wall reflectionsWall penetration followed by ground then ceiling reflectionsWall penetration followed by either (wall then ground reflections) or (ground then wall reflections) or (corner between ground and wall reflection)Wall penetration followed by three wall reflectionsWall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or
Case-4	A. Wall penetration	Path8 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8	 Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling then ground reflections Wall penetration followed by ground reflection Wall penetration followed by wall reflection Wall penetration followed by two wall reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by two wall reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by two wall reflections Wall penetration followed by either (wall then ground reflections) or (ground then wall reflections) or (corner between ground and wall reflection) Wall penetration followed by three wall reflections Wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and
Case-4	A. Wall penetration	Path9 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8	 Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling then ground reflections Wall penetration Wall penetration followed by ground reflection Wall penetration followed by wall reflection Wall penetration followed by ground then ceiling reflections Wall penetration followed by either (wall then ground reflections) or (ground then wall reflections) or (corner between ground and wall reflection) Wall penetration followed by three wall reflections Wall penetration followed by either (ground then ceiling reflections) or (from ground then ceiling then wall then ceiling reflections) or (from ground then ceiling reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)
Case-4	A. Wall penetration	Path9 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8 Path9 Path9	 Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling then ground reflections Wall penetration Wall penetration followed by ground reflection Wall penetration followed by wall reflection Wall penetration followed by two wall reflections Wall penetration followed by ground then ceiling reflections Wall penetration followed by either (wall then ground reflections) or (ground then wall reflections) or (corner between ground and wall reflection) Wall penetration followed by three wall reflections Wall penetration followed by either (ground then ceiling reflections) or (from ground then ceiling then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection)
Case-4	A. Wall penetration B. Partial wall	Path9 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8 Path9 Path1 Path1 Path2	 Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling then ground reflections Wall penetration Wall penetration followed by ground reflection Wall penetration followed by wall reflection Wall penetration followed by two wall reflections Wall penetration followed by ground then ceiling reflections) or (ground then wall reflections) or (corner between ground and wall reflection) Wall penetration followed by three wall reflections Wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall penetration followed by ground then ceiling then ground reflections Partial wall penetration
Case-4	A. Wall penetration B. Partial wall penetration	Path9 Path9 Path1 Path2 Path3 Path4 Path5 Path6 Path7 Path8 Path8 Path9 Path1 Path2 Path1 Path2 Path3	 Wall-ceiling penetration Ceiling-wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall-ceiling penetration followed by ground then ceiling then ground reflections Wall penetration Wall penetration followed by ground reflection Wall penetration followed by wall reflections Wall penetration followed by ground then ceiling reflections) or (ground then wall reflections) or (corner between ground and wall reflection) Wall penetration followed by three wall reflections Wall penetration followed by either (ground then wall then ceiling reflections) or (from ground then ceiling then wall then ceiling reflections) or (from ground then ceiling then wall then reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall penetration followed by ground then ceiling then ground reflections) or (wall then ground then ceiling reflections) or (corner between ground and wall reflection then ceiling reflection) Wall penetration followed by ground then ceiling then ground reflections Partial wall penetration followed by ground reflection Partial wall penetration followed by ground reflection
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Figure-2. Elevation angles of incident rays.

In the following derived equations for the 8 cases, the quantities Δx and Δy are the horizontal and vertical ray shifts, when a ray penetrate through ceiling or wall, L₁ is the ray length when the ray passes through the concrete walls, and parameter L₂ is the virtual ray length without the brokenness that occur during crossing the concrete wall. Parameter δ is the skin depth. For parameters ($T_{S1}, T_{S2}, T_{h1}, T_{h2}$), T refers to the transmission coefficient, s refers to soft polarization, h hard polarization, subscript 1 indicates ray transmitted from air to the concrete building, subscript 2 ray transmitted from concrete walls to inside the room. For parameters ($R_{g}^{s}, R_{g}^{h}, R_{b}^{s}, R_{b}^{s}$), R refers to the reflection coefficient, superscript s refers to soft polarization, h hard polarization, subscript g refers to ground, and b to the building (room). For parameters $(D_A^{S}, D_A^{h}, D_B^{S}, D_B^{h})$, D refers to the diffraction coefficient, superscript s refers to soft polarization, h hard polarization, subscripts A and B are diffraction points shown in Figure-1.

As the paper length does not permit the presentation of the equations for all the 70 rays described in Table-2, we present below a sample ray path for each of the 8 cases.

Case-1: Ceiling Penetration

In case-1, rays penetrate concrete ceiling before reaching mobile antenna in 9 paths.

Path-1: Ceiling penetration is illustrated in Figure-3.



Figure-3. Configuration for ray penetrating the concrete ceiling.

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$$\mathbf{E}^{i}\mathbf{1}(mobile) = \mathbf{E}_{o}\mathbf{T}_{s1}(\theta_{i})\mathbf{T}_{s2}(\theta_{i})e^{\frac{-t}{\delta\cos\theta_{i}}}e^{-jk_{o}(r_{1}-L_{1})}e^{-jkL_{1}}\frac{1}{r_{1}}$$
(1)

$$H^{i}1(mobile) = H_{o}T_{h1}(\theta_{i})T_{h2}(\theta_{i})e^{\frac{-r}{\delta\cos\theta_{i}}}e^{-jk_{o}(r_{1}-L_{1})}e^{-jkL_{1}}\frac{1}{r_{1}}$$

Where

$$r_{1} = \sqrt{(x_{bs} + t + x_{m1} + \Delta x)^{2} + (h_{bs} - h_{m})^{2} + L_{1} - L_{2}},$$

$$L_{1} = \frac{t}{\cos \theta_{t}}, \quad L_{2} = \frac{t}{\cos \theta_{i}} \quad \text{and} \quad \Delta x = t(\tan \theta_{i} - \tan \theta_{t})$$

Case-2: Ceiling - Wall Penetration

In case (2), rays are incident on ceiling and penetrate the wall then reach the mobile by 9 paths.

Path-2: Ceiling-wall penetration followed by ground reflection is shown in Figure-4.



$$E^{i}2(mobile) = E_{o}T_{s1}(\theta_{i})T_{s2}(\frac{\pi}{2} - \theta_{i})R_{g}^{s}(\theta_{i})e^{\frac{-t}{\delta\cos\theta_{i}}}e^{-jk_{o}(r_{2} - L_{1})}e^{-jkL_{1}}\frac{1}{r_{2}}$$
(3)

$$H^{i}2(mobile) = H_{o}T_{h1}(\theta_{i})T_{h2}(\frac{\pi}{2} - \theta_{i})R_{g}^{h}(\theta_{i})e^{\frac{-t}{\delta\cos\theta_{i}}}e^{-jk_{o}(r_{2} - L_{1})}e^{-jkL_{1}}\frac{1}{r_{2}}$$
(4)

Where:



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Case-3: Wall - Ceiling Penetration

In case-3, rays incident on wall penetrate the ceiling then reach the mobile by 9 paths.

Path- 3: Wall-ceiling penetration followed by wall reflection is depicted in Figure-5.



Figure-5. Configuration for ray incidence on ceiling then penetrated from concrete wall followed by wall reflection.

$$E^{i} 3(mobile) = E_{o} T_{s1}(\theta_{i}) T_{s2}(\frac{\pi}{2} - \theta_{i}) R_{b}^{s}(\theta_{i}) e^{\frac{-t}{\delta \cos \theta_{i}}} e^{-jk_{o}(r_{3} - L_{1})} e^{-jkL_{1}} \frac{1}{r_{3}}$$
(5)

$$H^{i} 3(mobile) = H_{o} T_{h1}(\theta_{i}) T_{h2}(\frac{\pi}{2} - \theta_{i}) R_{b}^{h}(\theta_{i}) e^{\frac{-t}{\delta \cos \theta_{i}}} e^{-jk_{o}(r_{3} - L_{1})} e^{-jkL_{1}} \frac{1}{r_{3}}$$
(6)

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Where

$$r_{3} = \sqrt{(x_{bs} + t + x_{m1} + 2x_{m2} - \Delta x)^{2} + (h_{bs} - h_{m})^{2}} + L_{1} - L_{2}$$
$$L_{1} = \frac{t}{\cos \theta_{t}} \quad L_{2} = \frac{t}{\cos \theta_{i}} \quad \Delta x = t(\tan \theta_{i} - \tan \theta_{t})$$

Case-4: Wall and Partial Wall Penetration

In case-4, the ray either A. penetrates the side wall or, B. penetrates part of the side wall, before reaching the mobile. Due to space limitations, only a sample of B will be given below.

B. Partial wall penetration: rays partially penetrate wall then reach mobile by 7 paths.

Path-4: Partial wall penetration followed by ground then ceiling reflections, as in Figure-6.



Figure-6. Configuration for ray partially penetrating wall followed by ground then ceiling reflections.

$$E^{i}4(\text{mobile}) = E_{o}T_{s1}(\theta_{i})T_{s2}(\frac{\pi}{2} - \theta_{t})R_{g}^{s}(\alpha)R_{b}^{s}(\alpha)e^{\frac{-t}{\delta\cos\theta_{t}}}e^{-jk_{o}(r_{4} - L_{1})}e^{-jkL_{1}}\frac{1}{r_{4}}$$
(7)

$$\mathrm{H}^{i}4(\mathrm{mobile}) = \mathrm{H}_{o}\mathrm{T}_{h1}(\theta_{i})\mathrm{T}_{h2}(\frac{\pi}{2} - \theta_{i})\mathrm{R}_{g}^{h}(\alpha)\mathrm{R}_{b}^{h}(\alpha)\mathrm{e}^{\frac{-\mathrm{t}}{\delta\cos\theta_{i}}}\mathrm{e}^{-\mathrm{j}k_{o}(r_{4} - L_{1})}\mathrm{e}^{-\mathrm{j}kL_{1}}\frac{1}{r_{4}}$$

 $r_{4} = \sqrt{(x_{bs} + t + x_{m1} - \Delta x)^{2} + (h_{bs} - h_{m} + 2(h_{b} - t))^{2}} + L_{1} - L_{2}$

Where

 $L_1 = \frac{h_{bs} - h_g - x_{bs} \tan \theta_i}{\sin \theta_t}$

 $L_2 = \frac{h_{bs} - h_g - x_{bs} \tan \theta_i}{\sin \theta_i}$

$$\Delta x = \left(h_{bs} - h_g - x_{bs} \tan \theta_i \left(\frac{1}{\tan \theta_t} - \tan\left(\frac{\pi}{2} - \theta_i\right)\right)\right)$$

In this case, rays enter the room directly from opened door and reach the mobile by 7 paths.

ceiling reflections, as in Figure-7.

Path-4: Through opened door followed by ground then

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Figure-7. Configuration for ray entered the door, reflected from ground, then reflected from ceiling.

$$E^{i}4(\text{mobile}) = E_{o}R_{g}^{s}(\theta_{i})R_{b}^{s}(\theta_{i})e^{-jk_{o}r_{4}}\frac{1}{r_{4}}$$

$$H^{i}4(\text{mobile}) = H_{o}R_{g}^{h}(\theta_{i})R_{b}^{h}(\theta_{i})e^{-jk_{o}r_{4}}\frac{1}{r_{4}}$$
(9)
(10)

Where

$$r_4 = \sqrt{(x_{bs} + t + x_{m1})^2 + (h_{bs} - h_m + 2(h_b - t))^2}$$

Case-6: Ground Reflection then Wall End Reflection or Penetration

In case-6, rays are reflected from ground, then reflected from wall end or penetrate it, before reaching mobile by 5 paths.

Path-2: Ground reflection then wall end reflection followed ground reflection, as in Figure-8.



Figure-8. Configuration for ray reflected from ground followed by wall end then ground reflections.

$$E^{i}2(\text{mobile}) = E_{o}R_{g}^{s}(\theta_{i})R_{b}^{s}(\theta_{i})R_{g}^{s}(\theta_{i})e^{-jk_{o}r_{2}}\frac{1}{r_{2}}$$

$$H^{i}2(\text{mobile}) = H_{o}R_{g}^{h}(\theta_{i})R_{b}^{h}(\theta_{i})R_{g}^{h}(\theta_{i})e^{-jk_{o}r_{2}}\frac{1}{r_{2}}$$
(11)

$$r_2 = \sqrt{(x_{bs} + t + x_{m1})^2 + (h_{bs} + h_m + 2h_g)^2}$$

Case-7: Ground Reflection then Wall Penetration

In this case, rays reflected from ground penetrate wall then reach mobile antenna by 3 paths.

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Path-3: Ground reflection then wall penetration followed

by ceiling then ground reflections, as shown in Figure-9.

$$E^{i}3(\text{mobile}) = E_{o}T_{s1}(\theta_{i})T_{s2}(\theta_{i})R_{g}^{s}(\alpha)R_{b}^{s}(\alpha)R_{g}^{s}(\alpha)e^{\frac{-t}{\delta\cos\theta_{i}}}e^{-jk_{o}(r_{3}-L_{1})}e^{-jkL_{1}}\frac{1}{r_{3}}$$
(13)

$$H^{i}3(\text{mobile}) = H_{o}T_{h1}(\theta_{i})T_{h2}(\theta_{i})R_{g}^{h}(\alpha)R_{g}^{h}(\alpha)R_{g}^{h}(\alpha)e^{\frac{-t}{\delta\cos\theta_{i}}}e^{-jk_{o}(r_{3}-L_{1})}e^{-jkL_{1}}\frac{1}{r_{3}}$$
(14)

Where

$$r_{3} = \sqrt{(x_{bs} + t + x_{m1})^{2} + (h_{bs} + h_{m} + 2(h_{b} - t) + \Delta y)^{2}} + L_{1} - L_{2}$$
$$L_{1} = \frac{t}{\cos \theta_{t}} \quad L_{2} = \frac{t}{\cos \theta_{i}} \quad \Delta y = t(\tan \theta_{i} - \tan \theta_{t})$$



Figure-9. Configuration for ray reflected from ground, penetrated wall followed by ceiling then ground reflections.

Case-8: Diffracted Rays Contributions

In case-8, all diffracted rays that reach mobile antenna are derived using one diffraction, and a maximum of two reflections. The total number of diffracted paths is 12. In equations of this case, parameters are defined as follows: s_1 is the distance between base station antenna and diffraction point, s_2 is distance between mobile antenna and diffraction point, \emptyset is incidence angle, \emptyset is the diffraction angle, and A and B are the diffraction points shown in Figure-1.

Path-10: Ground reflection followed by diffraction from inner edge for door then wall reflection is illustrated in Figure-10.

$$E^{i}10(mobile) = E_{o} \frac{e^{-jk(s_{1}+s_{2})}}{s_{1}} D_{B}^{s} R_{g}^{s} \left(\frac{\pi}{2} - \tan^{-1}\left(\frac{h_{bs} + h_{g}}{x_{bs} + t}\right)\right) R_{b}^{s} \left(\sin^{-1}\left(\frac{h_{g} - h_{m}}{s_{2}}\right)\right) \sqrt{\frac{s_{1}}{s_{2}(s_{1} + s_{2})}}$$
(15)

$$H^{i}10(mobile) = H_{o} \frac{e^{-jk(s_{1}+s_{2})}}{s_{1}} D_{B}^{h} R_{g}^{h} \left(\frac{\pi}{2} - \tan^{-1}\left(\frac{h_{bs} + h_{g}}{x_{bs} + t}\right)\right) R_{b}^{h} \left(\sin^{-1}\left(\frac{h_{g} - h_{m}}{s_{2}}\right)\right) \sqrt{\frac{s_{1}}{s_{2}(s_{1} + s_{2})}}$$
(16)

$$s_{1} = \sqrt{(x_{bs} + t)^{2} + (h_{bs} + h_{g})^{2}} \quad s_{2} = \sqrt{(x_{m1} + 2x_{m2})^{2} + (h_{g} - h_{m})^{2}}$$
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Figure-10. Configuration for ray reflected from ground followed by edge B diffraction then wall reflection.

4. BASE STATION ANTENNA RADIATION

The basic function of a macrocell base station antenna is to provide uniform coverage in the azimuth plane. In addition it provides directivity in the vertical plane by means of vertical array of dipoles. In order to direct the radiated power to the ground rather than the sky, the array antenna is tilted downward by "Tilt angle". Usually, main beam of the radiation pattern is directed to a horizontal distance of about 150 m on the ground [13] as shown in Figure-11. In view of that,

$${\rm tilt\,angle} = {\rm tan^{-1}} \Big(\frac{{\rm base \ station \ height}}{{\rm distance \ at \ which \ beam \ strikes \ earth}} \Big) = {\rm tan^{-1}} \Big(\frac{{\rm 30}}{{\rm 150}} \Big) ~ \approx ~ 11^{\circ}$$

An antenna array consisting of 4 half-wave dipoles is assumed, along with conducting back plane placed at $\lambda/8$ from the dipoles. Using pattern multiplication theorem [14], the base station antenna radiation pattern is the product of half-wavelength dipole pattern and the array factor:

$F(\theta) = \cos(\pi/2)\cos(\theta - 0.192)]/(\sin(\theta - 0.192)) = \sin(\pi/2)\cos(\theta - 0.192))/(\sin(\theta - 0.192))/(2) = \sin(\pi/2)\cos(\theta - 0.192) + \pi/2)/(2) = \sin(\pi/2)\cos(\theta - 0.192)/(2) = \sin(\pi/2)\cos(\theta - 0.192))/(2) = \sin(\pi/2)\cos(\theta - 0.192)/(2) = \sin$

where the tilt angle is $11^\circ = 0.192$ rad, thus the main beam is directed at $\theta = 101^\circ$ from the z-axis as shown in Figure-12.

Radiated wave polarization

The base station antenna in cellular communications is polarized vertically to cover a large area. We have also considered horizontal and circular polarization transmissions. The reflection and diffraction coefficients of horizontal and vertical polarizations are not the same. This means that the relative magnitudes of the two reflected or diffracted signal components (horizontal and vertical) will change. Consequently, there is depolarization (polarization distortion) and circular polarization signal becomes elliptically polarized. The electric field vector E of elliptically polarized signal is composed of x and y linearly polarized components with amplitudes E_x and E_y and phase angles arg (E_x) and arg (E_y). The axial ratio AR is given by [13]:

$$AR = \left[\frac{1 + \left|\frac{E_y}{E_x} cos[\arg(E_y) - \arg(E_x)]\right|^2}{\left|\frac{E_y}{E_x} sin[\arg(E_y) - \arg(E_x)]\right|}\right]^{\frac{1}{2}}$$

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Figure-11. Base station antenna tilt angle.



Figure-12. Radiation pattern of base station antenna with 11° tilt angle; θ is measured from positive z-axis.

5. RESULTS

In our simulations, normalized signal strength for soft and hard polarizations, cumulative distribution function (CDF), probability density function (PDF), and the axial ratio (AR) of the received signal at a mobile terminal moving inside a room are studied at three different base station locations from the room: 10m, 180m, and 2000m. The transmitted fields from the base station are normalized (set to unity value) at 1 m away from the transmitting base station antenna. We have verified the computer programs before obtaining results, by computing the received signal when the elevation angle is equal to $0.0143^{\circ} \approx 0^{\circ}$. Since room length is 4m and the wave frequency is 900 MHz (wave length of 1/3 m), the signal pattern exhibited a clear resonance with 6 half wavelengths in each meter length inside the room. We cannot choose an elevation angle equals to zero because in this case we must assume that the tower height is at the same height of the mobile, and that is not valid in our algorithm.

Although when the base station is at 180m from the room, the signal travels much farther distance than the situation when the base station is at 10m, the received signal strength is higher for 180 m distance, as shown in Figure-13. This is because the main beam is directed towards the 180 m distance. Also the signals received from the base station located at 10m suffer from more attenuation because they penetrate the concrete walls, while most of the received signals from the base station when it is located at 180m pass through the opened door. For the 2000 m distance, the received signal is also significantly lower than the 180 m distance due to the much larger free space attenuation for the 2000 m distance, in addition to the fact that the main beam is not directed towards this distance.



Figure-13. Normalized signal strength for soft polarization signal at x_{bs} =10m, 180m, 2000m.

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Comparison with measurements

Figure-14 shows the comparison between measured [15] and calculated received signal in dBm, for distances between the base station and the mobile up to 400m, with the base station height of 7m and the mobile height of 2m, and the frequency of the transmitted signal is 915 MHz. The system parameters such as transmitted power levels, antenna gains, and receiver gains are normalized. There is a good agreement between calculated and measured results. Ripples in the received signal, for distances less than 100 m, are attributed to the constructive and destructive interferences between the direct and reflected ray paths. Nevertheless, the general trend is that the signal decreases as the distance increases. The measurements were performed for line of sight between the base station and the mobile in a quiet residential area where houses had only one floor with front yard and with no traffic in the street. Therefore, our calculations for this example is based on line of sight communications between the base station and mobile phone which is now located outside the room.



Figure-14. Calculated and measured signal power at mobile phone vs. distance from base station, with h_{bs} =7m, h_m =2m, f= 915 MHz.

CDF and PDF

Most of the statistical models of land mobile communication channels use predefined probability density functions (PDFs) such as Gaussian and Rayleigh PDFs to model the received signal amplitude [18]. In this paper, CDF and PDF characterizing the communication link between base station and mobile inside concrete room are derived from the computed received signal. These CDF and PDF based on robust modeling should better represent the channel than an assumed predefined CDF and PDF. Figure-15 shows CDF for soft polarization received signal at three different locations from the base station x_{bs} = (10m, 180m, 2000m). Figure-16 gives PDF for soft polarization received signal at 180m from the base station. The PDF of the received signal is the derivative of CDF.



Figure-15. Cumulative distribution function CDF for normalized signal strength, for soft polarization, at $x_{bs} = (10m, 180m, 2000m)$.



Figure-16. Probability density function for soft polarization, at $x_{bs} = 180$ m.

Depolarization effects

Figure-17 shows the axial ratio versus mobile distance inside the room when the base station is located at 180m away. Although the transmitted signal is circularly polarized (0 dB axial ratio), the received signal is elliptically polarized (axial ratio > 0 dB) as shown in Figure-17. This is due to multiple reflections and diffractions and attenuation of the signal, which causes a relatively large difference in the values of soft and hard polarization signals. This introduces extra losses in the link budget and subsequently deteriorates the system performance. Depolarization effect must be treated by accounting for its losses in the link budget or introducing new requirements for mobile antenna to adjust the polarization characteristics of the propagation environment.



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Figure-17. Axial ratio vs. mobile distance x_{m1} inside the room for x_{bs} =180 m.

CONCLUSIONS

In this paper, propagation model for macrocellular wireless communication systems is presented. This model is applied to characterize the base station to mobile transmitted signal under the effect of concrete building blockage where the mobile is located inside this building or room. The signal analysis was performed using ray tracing techniques and the uniform theory of diffraction (UTD), all significant ray paths that reach to the moving mobile from the base station antenna have been derived. Comparison with measured data revealed acceptable agreement. In this study, base station radiations were analyzed for different distances from the room; short, middle, and far distances, i.e., 10m, 180m, and 2000m. Different computer programs were written using Matlab to implement this model. Horizontal, vertical, and circular polarizations are considered. Quantities useful for the design of wireless communication system, such as cumulative distribution function, probability density function, and axial ratio are computed. Diffractions from the edges of the building in addition to multiple reflections from ground, building walls and ceiling, result in depolarization of the transmitted signal. This effect causes mismatching between the transmitted signal and the mobile antenna.

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