Characterizing and Modelling of Indoor Radio Pr opagation Channel at ISM Band

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Abstract: The investigation of the indoor electromagnetic propagation has been performed at the unlicensed industrial, scientific, and medical (ISM) band, which has gained increased attention recently due to high data rate communication systems developed to operate in it. The effect of the incidence angle and materials thicknesses on the reflection coefficients for both horizontal and vertical polarization has been studied. Two-dimensional ray-tracing model has been suggested to simulate the influence of buildings electromagnetic properties on indoor radio channel characteristics, such as signal level, rms delay spread, and coherence bandwidth. Results show that the influence of the permittivity is more important than the influence of the order of reflection considered for the ray- tracing model. It is also shown that, compared with power level, rms delay spread is more sensitive to the building dielectric parameters. Maximum rms delay spread is dependent mainly on the reflectivity of the walls which dependent on the dielectric parameters.

توصيف ونمذجة قناة انتشار راديوية داخلية في حزمة أي أس أم

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الخلاصة:
تمت دراسة وتقصي الانتشار الداخلي للموجات الكهرومغناطيسية في حزمة (أي-أس-ام) التي اكتسبت اهمية كبيرة في الاونة الاخيرة خصوصا في تشغيل انظمة الاتصالات الشخصية والشبكات المحلية اللاسلكية داخل المباني. ولقد تمت دراسة تاثير زاوية السقوط، وسمك مواد البناء على معاملات انعكاس الموجات الكهرومغناطيسية في حالتي الاستقطاب الافقي والعمودي. ولقد تم اقتراح نموذج تتبع ثنائي الابعاد للشعاع الكهرومغناطيسي لغرض حساب تأثير الخصائص الكهرومغناطيسية للمباني على طبيعة الانتشار الداخلي للموجات الكهرومغناطيسية، وتم حساب مستوى قدرة الاشارة، تشتت التاخير الفعال، وعرض الحزمة المتماسك. واظهرت النتائج بان تشتت التاخير الفعال يكون أكثر حساسية للخصائص الكهرومغناطيسية لمواد البناء واعتماده اساسا على مدى انعكاسيتها.

1. Introduction:

Analysis of indoor radio channel characteristics is important for the design and development of personal commun-ication systems and Wireless Local Area Networks (WLANs), which have been allocated unlicensed Industrial, Scientific, and Medical (ISM) frequency band at 2.4 GHz. To develop such systems, examination of the mechanisms of electromagnetic wave propagation and the effect of the electromagnetic properties of building materials at this band is required. Radio propagation in the indoor radio channel is affected by the layout in the building, especially the use of different building materials. Owing to reflection, refraction and diffraction of radio waves by objects such as walls, windows, doors and furniture inside the building, the direct path from transmitter to receiver is often blocked and there are many additional signal paths present due to reflections off of the walls, floors, and ceilings of the building [1]. Effects of these propagation mechanisms on the radio wave are determined by the electromagnetic properties of those surrounding structures. Therefore to obtain accurate channel characteristics, a good knowledge of their electromagnetic properties is required.

For indoor channel characterization, the path loss is a parameter that can predict the power level of the system and the space coverage of the base station, while *rms* delay spread is a good measure of channel multipath spread and can give an indication of the potential for inter- symbol interference [2]. The delay spread is therefore an essential parameter in the design of wireless communication systems.

In this paper, a model based on multiple successive internal reflections inside a material slab has been successfully used to simulate the reflection coefficients as functions of the incident angle and to describe the reflection mechanisms for smooth surfaces of thicknesses not too large compared to the wavelength. The effect of electromagnetic parameters on indoor radio channel characteristics has been performed by using two-dimensional ray tracing model. It is worth mentioning that the dielectric material properties (permittivities and conductivities) for the materials used in this paper were taken from the measurements carried out previously by the author of this paper at the same band [3].

The characterization of horizontally and vertically polarized reflection coefficients for different materials as a function of incidence angle are discussed in Section-2. Ray tracing model has been suggested in Section-3 to predict and simulate the different radio channel parameters such as power level, *rms* delay spread, and coherence bandwidth in indoor environments. The main concluding remarks are listed in Section-4.

2. Reflection Coefficients Characterization:

The reflection coefficient from a smooth surface can be divided into two factors: one for horizontal polarization (Γ_h), and the other for vertical polarization (Γ_v), and they are given by [4]:

$$\Gamma_h = \frac{\sin(\theta) - \sqrt{\varepsilon - \cos^2(\theta)}}{\sin(\theta) + \sqrt{\varepsilon - \cos^2(\theta)}} \qquad (1)$$

$$\Gamma_v = \frac{\varepsilon\sin(\theta) - \sqrt{\varepsilon - \cos^2(\theta)}}{\varepsilon\sin(\theta) + \sqrt{\varepsilon - \cos^2(\theta)}} \qquad (2)$$

where θ is the angle of incidence and ε is the complex permittivity given by $\varepsilon = \varepsilon_r - j60\sigma\lambda$, and ε_r is the normalized relative dielectric constant of the reflecting surface, σ is the conductivity of the reflecting surface, and λ is the wavelength of the incident ray.

When the thickness of the material (l) is not too large compared with the wavelength, equations (1), and (2) may lead to significant errors. In this case, each incident ray to such material rise to multiple reflected and transmitted rays, and the strength of these rays are functions of the material and its thickness as well as the signal frequency and the angle of incident ray. Thus the reflection characteristics of the material can be explained using multi ray model as shown in Fig.1, and the overall reflection coefficients Γ_t are given by [5]:

$$\Gamma_t = \Gamma - (1-\Gamma^2)\frac{\Gamma\, e^{-j2ks} e^{-2\alpha s} e^{jk_0 d\cos(\theta)}}{1-\Gamma^2 e^{-j2ks} e^{-2\alpha s} e^{jk_0 d\cos(\theta)}} \quad (3)$$

where Γ is either the horizontal or vertical reflection coefficient as given by equations (1) and (2) respectively, k is the propagation constant inside the material given by:

$$k = \frac{2\pi}{\lambda}\sqrt{\varepsilon_r} \quad (3a)$$

α is the attenuation constant inside the material given by:

$$\alpha = \frac{\omega\tan(\delta)}{2}\sqrt{\mu_o\varepsilon_r\varepsilon_o} \quad (3b)$$

ω is the angular frequency, $\tan(\delta)$ is the loss tangent of the material, μ_o & ε_o are the free space permeability and permittivity respectively, and k_o is the free space propagation constant given by:

$$k_o = \frac{2\pi}{\lambda} \quad (3c)$$

s is the path length inside the material between the two surfaces given by:

$$s = \frac{l}{\sqrt{1-\frac{\cos^2(\theta)}{\varepsilon_r}}} \quad (3d)$$

d is the path length difference on the material of two consecutive departing reflections given by:

$$d = \frac{2l}{\sqrt{\frac{\varepsilon_r}{\cos^2(\theta)}-1}} \quad (3e)$$

Four various types of building materials were used to study the characterization of reflection coefficients as a function of the incidence angle. These materials are: 12mm glass, 8mm chipwood, 38mm thickwood, 40mm wooden door. It is clear that the thicknesses of these materials are less than the wavelength, thus the multi ray model can be used to simulate the reflection coefficients. The electromagnetic characteristics of the above materials were taken from [3] at 2.4 GHz and shown in Tables (1) and (2) for vertical and horizontal polarization respectively.

Figure 2 shows the magnitude of the reflection coefficients as a function of incidence angle for both horizontal and vertical polarization for the above mentioned four materials.

To estimate the degree of reflection coefficient variation, reflection coefficient is simulated as a function of materials thickness for a given values of incidence angle. Fig. 3 shows reflection coefficient variations for glass at 10^o, and 50^o incident angle respectively for both horizontal and vertical polarization.

3. Ray Tracing Model and Results:

Recently the ray-tracing technique has been used widely to predict radio channel in indoor environments. In this paper, we consider the transmitter and receiver both have vertically polarized omnidirectional antennas and the antenna pattern prevents strong components from being reflected from the ceiling or the floor. As a result, only the paths from the walls will contribute significantly to the received signal. To find all the paths under these circumstances, we need only trace the paths in two dimensions. Fig. 4 shows a two-dimensional map of the inside walls of a room under line of sight (LOS) condition and first, second, third order reflected paths [6].

For the purpose of modeling, a (30m X 15m) rectangular room is centered at the origin in the x-y plane and the transmitter and receiver are placed at (x_t, y_t) and (x_r, y_r) respectively. The receiver and its images lie at the points $((-1)^n x_r + na, (-1)^m y_r + mb)$ for integers n and m, where a and b are the dimensions of the room. A ray reaching the $nmth$ image undergoes $|n|+|m|$ reflections, and the distance from the transmitter to an image is given by [7]:

$$d_{nm}^2 = ((-1)^n x_r + na - x_t)^2 + ((-1)^m y_r + mb - y_t)^2 \quad (4)$$

This model can be used to predict the following different indoor channel parameters:

i- Power Level P_{nm}: In indoor environment, the composite received signal is the sums of the signals arriving along different paths. Except for the LOS paths, all paths are going through at least one order of reflection before arriving at the receiver. According to our model, the power in the ray at the nm-th image is equal to:

$$P_{nm} = P\frac{\Gamma^{2(n+m)}}{d_{nm}^2} \quad (5)$$

where P is a constant value, Γ represents the reflection coefficient given by equations (1) and (2). For the purpose of comparison, absolute values of the power are not required so it has not been determined for the data presented and only relative values of multipath power are given.

ii- *rms* Delay Spread τ_{rms}: In wideband system, most of multipath components are resolved and these time-delayed signals contribute to intersymbol interference τ_{rms}, which is used to quantify the time dispersion of wideband multipath channel. It gives an indication of maximum data rate that can be achieved without giving rise to intersymbol interference. The *rms* delay spread is given by the second moment of impulse response [5].

$$\tau_{rms} = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} \quad (6)$$

where $\overline{\tau^n}$ for given (L) propagation paths is as:

$$\overline{\tau^n} \equiv \frac{\sum_{i=1}^{L} \tau_i^n |P_i|^2}{\sum_{i=1}^{L} |P_i|^2} \qquad n = 1,2 \quad (6a)$$

where τ_i and P_i are the time delay and power of the *ith* path respectively.

iii- Coherence Bandwidth B_c: A dual representation of delay in terms of a frequency domain parameter is given by the coherence bandwidth B_c. The coherence bandwidth is inversely proportional to *rms* delay spread. Assuming frequency correlation between amplitudes of frequency components being above 0.9, coherence bandwidth can be approximated by [8].

$$B_c \approx \frac{1}{50\tau_{rms}} \quad (7)$$

Tables (3) and (4) show the effect of increasing the dielectric constants parameters (permittivity and conductivity) on the mean values of power level, rms delay spread, and coherence bandwidth for a given location of transmitter and receiver. The original values of permittivity and conductivity for concrete wall are as shown in Tables (1) and (2) for vertical and horizontal polarization respectively.

From Table (3) it is found that changes in permittivity value have little effect on the power level. In the other hand, the changes in permittivity values have significant impacts on channel *rms* delay spread. From Table (4) it is noted that the effect of changes in conductivity values is less significant compared to the changes in permittivity values. Most of building structures are low loss materials so that small variations of their conductivity values do not affect the channel characteristics significantly.

Simulations were also carried out when the order of reflection (the maximum number of reflections that are considered for each ray) is varied. Table (5) shows the effect of the reflection order on the *rms* delay spread for a given two arbitrary locations of transmitter and receiver, and for original values of dielectric parameters. It is shown that the delay parameters are closely related to the order of reflections, the larger this order, the larger the time delay is.

Figure (5) shows the fitted plot for power level against radial distance between transmitter and receiver for different values of permittivity. As it is expected, the power level decreases with the increasing of the distance between transmitter and receiver. Figure (6) shows the fitted plot for rms delay spread against radial distance between transmitter and receiver for different values of permittivity. It is seen that the *rms* delay spread increase with distance from the transmitter up to a maximum value that is thereafter constant with distance of the remainder of the room. The maximum value of the *rms* delay spread depends mainly on the reflectivity of the enclosing wall which is depends on the permittivity of the walls.

4. Conclusions

The reflection coefficients for various smooth building materials at ISM band as functions of the incidence angle have been calculated. From Fig.2, the results show that the reflection coefficients in the case of vertical polarization were smaller than those for horizontal polarization. Furthermore, they have values less than 0.1 at certain incidence angles. From Fig.3, it is generally observed that the reflection coefficient of a dielectric glass material fluctuates when the material is thin, and then converges to a steady value as the material thickness becomes thicker. The reason for this is that the signal decays as it propagates in the dielectric material, and consequently the contribution to the overall reflected signal is reduced.

Two dimensional ray-tracing model is used to study the effect of dielectric parameters on the indoor channel characteristics at ISM band. The influence of the order of reflections of the ray tracing model on the channel parameters is also investigated. The simulation tool makes use of the electromagnetic constants previously measured at this band [3]. It is shown that *rms* delay spread is more sensitive than power level to building dielectric parameters. The permittivity values have a capital importance in the relative amplitude of the reflected and transmitted rays. This influence leads to meaningful variations in the predicted values of the delay spread when these permittivity values are changed. The effects of changes in conductivity values are less significant than the changes in permittivity values.

The influence of electromagnetic parameters is more important than the order of reflection for the ray- tracing model. However, delay parameters are closely related to the order of reflections, the larger this order, the larger time delay.

The *rms* delay spread for a given area increases with the radial distance from transmitter up to a maximum value, which then remains constant across the remainder of the room. This maximum value depends mainly on the reflectivity of the enclosing walls, which is depends on the dielectric parameters.

References

[1] K. Tapan, C. M. Sarkar, C. W. Michal , S. P. Magdalena, and J. B. Robert, Smart Antennas, John Wiley and Sons, 2003.

[2] T. S. Rappaport , Wireless Communications Principles and Practice, Prentice Hall, 1996.

[3] Y. E. Mohammed, Y. A. Liu, A. S. Abdallah, "Estimation of Materials Characterization from Transmission Coefficient Measurements at 2.4GHz," Proceedings of the International Conference of Telecommunications ICT 2002, Beijing, China, Vol. 2, p.p. 357-360, Jun 2002.

[4] C. A. Balanis, Advanced Engineering Electromagnetic. New York, John Wiley and Sons, 1989.

[5] W. D. Burside, K. W. Burgener, " High Frequency Scattering by Thin Lossless Dielectric Slab," IEEE Transactions on Antennas and Propagation, Vol. AP-31, No. 1, Jan 1983.

[6] K. Pahlavan, A. H. Levesque, Wireless Information Networks. New York, John Wiley & Sons, 1995.

[7] J. T. E. McDonnell, T. P. Spiller, T.A. Wilkinson, "RMS Delay Spread in Indoor LOS Environments at 5.2 GHz," Electronics Letters, Vol. 34, No. 11, pp. 1149-1150, May. 1998.

[8] Y. P. Zhang, and Y. Hwang, "Time delay characteristics of 2.4 GHz band radio propagation channels in room environments," Proceedings IEEE 5th Personal Indoor and Mobile Radio Communications, The Hague, Netherlands, Vol.1, pp. 28-32, Sept. 1994.

Table (1): Materials characterization for vertical polarization

Material	$\varepsilon_s^{'}$	$\varepsilon_s^{''}$	$\tan(\delta)$	$\sigma(S/m)$
Glass	5.73	0.66	0.115	0.088
Chip wood	2.45	0.60	0.244	0.080
Thick wood	4.22	0.41	0.097	0.054
Door	5.91	0.23	0.038	0.030
Concrete wall	3.52	0.21	0.059	0.028

Table (2): Materials characterization for horizontal polarization

Material	$\varepsilon_s^{'}$	$\varepsilon_s^{''}$	$\tan(\delta)$	$\sigma(S/m)$
Glass	5.70	0.55	0.096	0.073
Chip wood	2.65	0.48	0.180	0.064
Thick wood	4.75	0.38	0.080	0.050
Wooden Door	5.63	0.34	0.060	0.045
Concrete wall	4.12	0.11	0.026	0.014

Table (3): Channel parameters for different permittivity values

Parameter	Original ε_r	50% inc.	100% inc.
P_{nm} (dB)	-59.02	-58.17	-57.51
τ_{rms} (ns)	13.28	14.29	15.15
B_c (MHz)	1.50	1.39	1.32

Table (4): Channel parameters for different conductivity values

Parameter	Original σ	50% inc.	100% inc.
P_{nm} (dB)	-59.02	-59.01	-59.00
τ_{rms} (ns)	13.28	13.28	13.29
B_c (MHz)	1.50	1.50	1.50

Table (5): *rms* delay spread values for different reflection order

	Reflection Order		
τ_{rms} (ns) at:	2	3	4

Location *No. 1*	13.28	13.96	14.21
Location *No. 2*	13.23	13.77	14.01

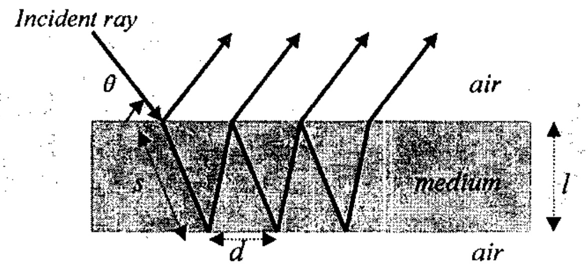


Fig.1: Reflections from a dielectric material slab

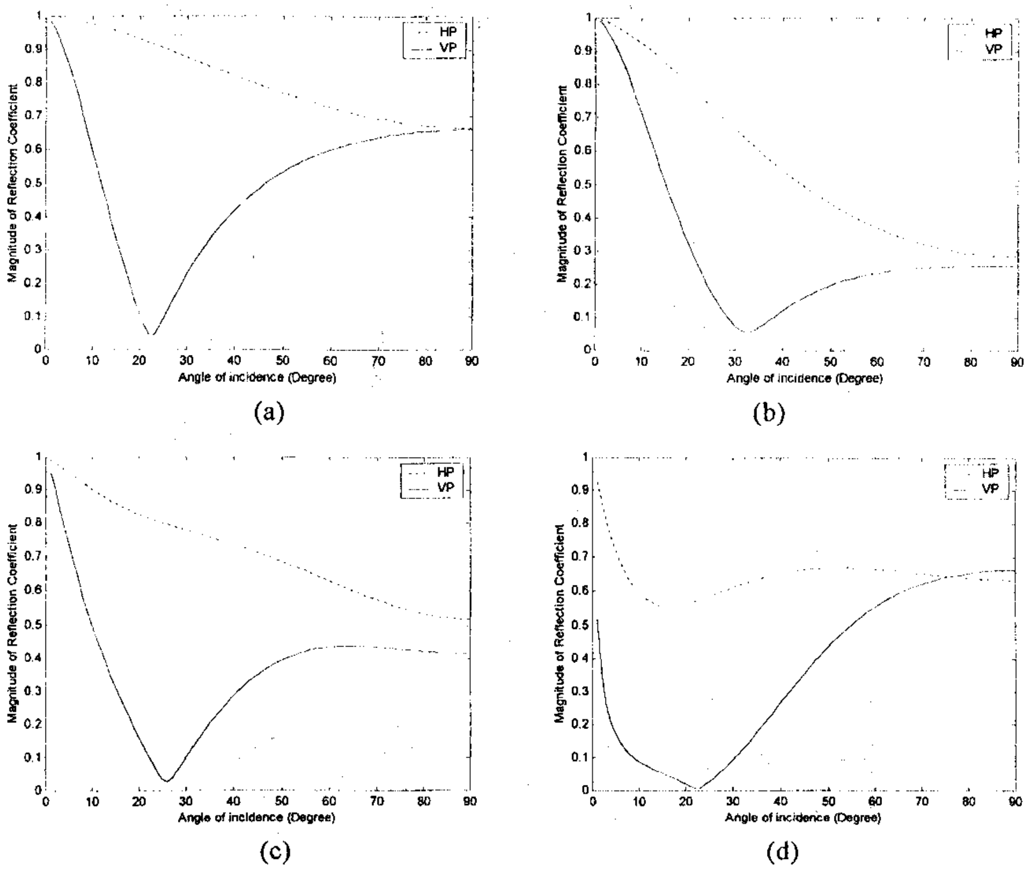
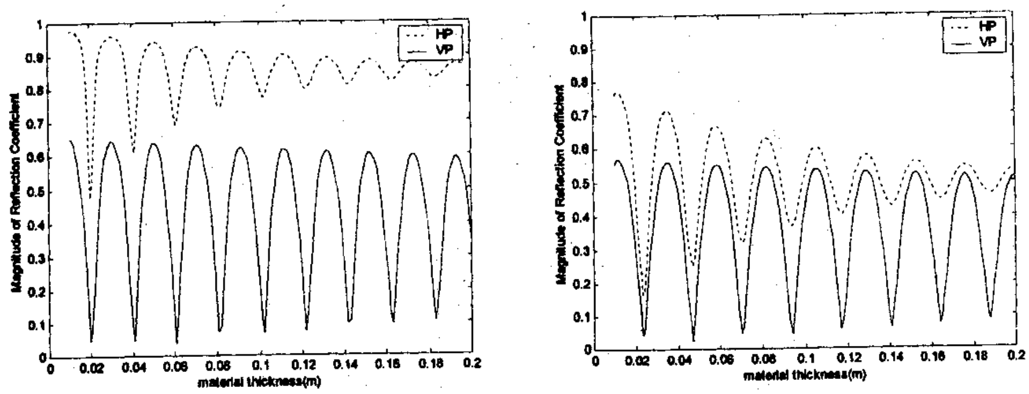


Fig.2: Reflection coefficients as a function of incident angle,
(a) 12mm glass, (b) 8mm chipwood, (c) 38 mm thickwood,
(d) 40mm wooden door



(a) (b)

Fig.3: Reflection coefficients as a function of the material thickness (glass)
(a) $\theta = 10^\circ$, (b) $\theta = 50^\circ$

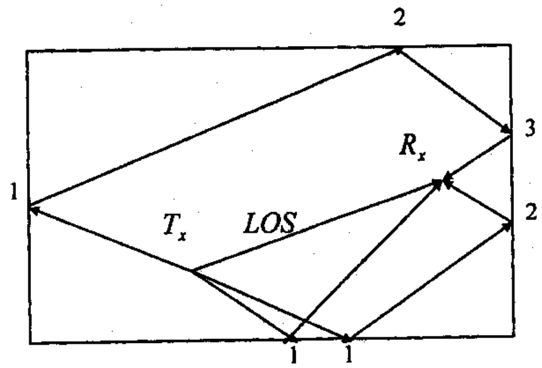


Fig.4: Reflections for ray tracing model in a rectangular room

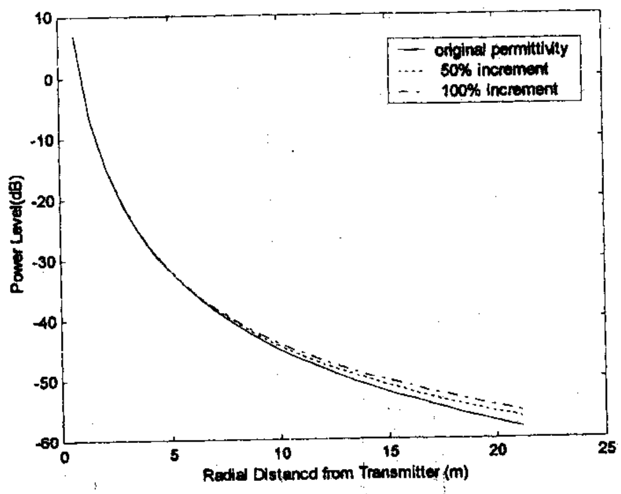


Fig.5: Power level against radial distance between transmitter and receiver

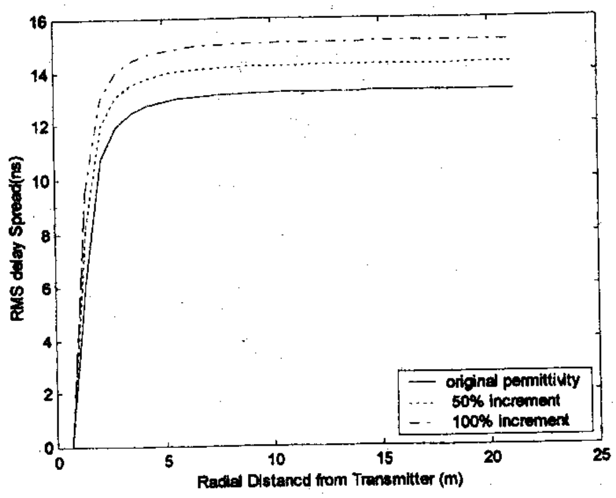


Fig.6: *rms* delay spread against radial distance between transmitter and receiver