



Recommendation ITU-R P.1410-5
(02/2012)

**Propagation data and prediction methods
required for the design of terrestrial
broadband radio access systems
operating in a frequency range
from 3 to 60 GHz**

P Series
Radiowave propagation



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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R P.1410-5

**Propagation data and prediction methods required for the design
of terrestrial broadband radio access systems operating
in a frequency range from 3 to 60 GHz**

(Question ITU-R 203/3)

(1999-2001-2003-2005-2007-2012)

Scope

Broadband wireless access is an important method of providing broadband to individual households as well as small business enterprises. This Recommendation addresses systems in a frequency range from 3 to 60 GHz and gives guidance for line-of-sight (LoS) coverage and non-LoS propagation mechanisms of importance. For affected systems, rain methods are given to estimate diversity improvement by selecting the best base station from two and the coverage reduction under rainfall. Guidance is given regarding wideband distortion.

The ITU Radiocommunication Assembly,

considering

- a) that for proper planning of terrestrial broadband radio access systems it is necessary to have appropriate propagation information and prediction methods;
- b) that Recommendations established for the design of individual links do not cover area aspects,

recommends

- 1** that the propagation information and prediction methods set out in Annex 1 should be used when designing terrestrial broadband radio access systems, operating in a frequency range from 3 to 60 GHz.

Annex 1**1 Introduction**

There is a growing interest in delivery of broadband services through local access networks to individual households as well as small business enterprises. Radio solutions are being increasingly considered as delivery systems, and these are now available on the market. Several systems are being considered and introduced, such as local multipoint distribution system (LMDS), local multipoint communications system (LMCS), and point-to-multipoint (P-MP) system. Collectively, these systems may be termed broadband wireless access (BWA). International standards are being developed, for example WMAX based on IEEE 802.16 and HiperMAN.

There is a need within the network planning, operator, and manufacturing communities and by regulators for good design guidance with respect to radiowave propagation issues.

2 Area coverage

When a cellular system is planned the operator has to carefully select base station location and height above the ground to be able to provide service to the target number of users within an area. The size of the cells may vary depending on the topography as well as on the number of users for which the radio service is being offered. This section presents a statistical model for building blockage based on very simple characterization of buildings in an area and provides guidance based on detailed calculations. It also presents a vegetation attenuation model and some simple design rules.

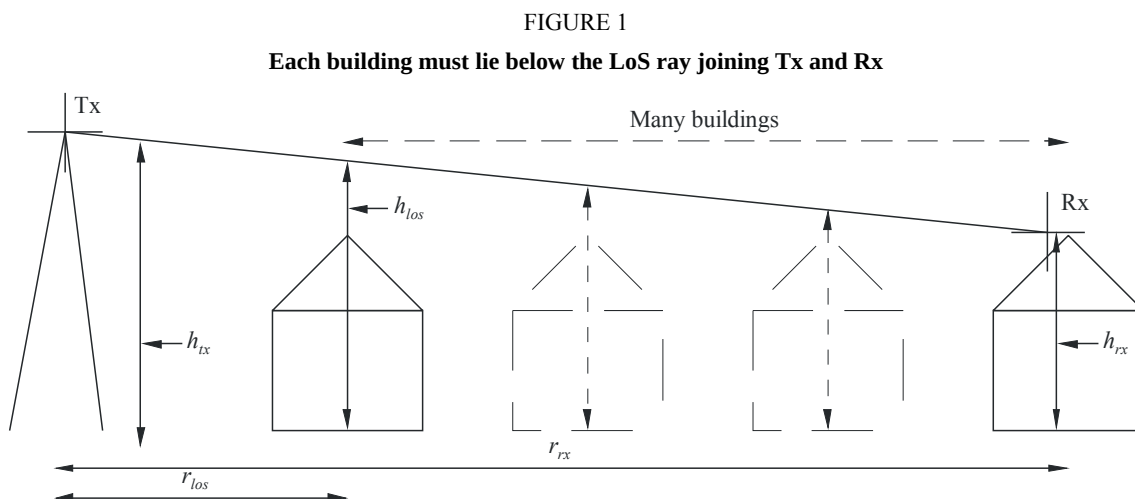
2.1 Building blockage

Building blockage probability is best estimated by ray-tracing techniques using real data from detailed building and terrain databases. The requirements for ray-tracing techniques are briefly described in § 2.1.1. However, in many areas, suitable databases are not available and the statistical model outlined in § 2.1.2 is recommended.

2.1.1 Ray-tracing requirements

An accurate coverage prediction can be achieved using ray-trace techniques in areas where a database of land coverage is available. Owing to the high frequency and short path lengths involved, straight line geometric optical approximations can be made.

To a first order of approximation in estimating coverage, an optical line-of-sight (LoS) determination of 60% of the 1st Fresnel zone clearance is sufficient to ensure negligible additional loss (see Fig. 1). Diffraction loss for non-LoS cases is severe. The accuracy of the buildings database will limit the accuracy of the ray prediction and the database must include an accurate representation of the terrain and buildings along the path. The Earth's curvature must also be considered for paths > 2 km. Buildings and vegetation should be considered as opaque for this procedure.



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Measurements of signal characteristics when compared against ray-trace models have shown good statistical agreement, but the measurements demonstrated considerable signal variability with position and with time for paths without a clear LoS. Therefore, owing to the limited accuracy of real building databases, predictions of service quality for specific near LoS paths will not be possible.

Vegetation, in particular tall trees and shrubs can cause severe service impairment and vegetation data should ideally be included in the database.

Measurements have indicated that, for service provision in a typical urban/suburban region, users impaired by multipath reflection effects are much rarer than those blocked by buildings or vegetation, owing to the narrow antenna beamwidth, and it is therefore not necessary to calculate reflections (see § 4.2.1).

The database used for ray-tracing evaluation may be a detailed object-oriented database, with terrain height, individual building outlines including roof height and shape data and with vegetation represented as individual trees or blocks of trees. As an alternative, in determining LoS, a raster database of spot height, such as generated from an airborne synthetic aperture radar (SAR) measurement may be used (see Table 1).

TABLE 1
Minimum database requirements

Object	Format	Horizontal resolution (m)	Vertical resolution (m)
Terrain	Grid of spot heights	50	1
Buildings	Object oriented or high resolution raster image	1	1
Vegetation			

2.1.2 Dealing with reflections and scattering

In an urban environment reflections off nearby buildings can be the dominant propagation mechanism in non-LoS conditions. Efficient methods to calculate reflections in large databases have been the subject of much research and literature. When considering multiple reflections and diffractions the problem becomes intractable for all but the most trivial of scenarios. For this reason a single-bounce reflection model, with each path to and from the reflector being subject to its own vertical and horizontal diffractions losses is recommended.

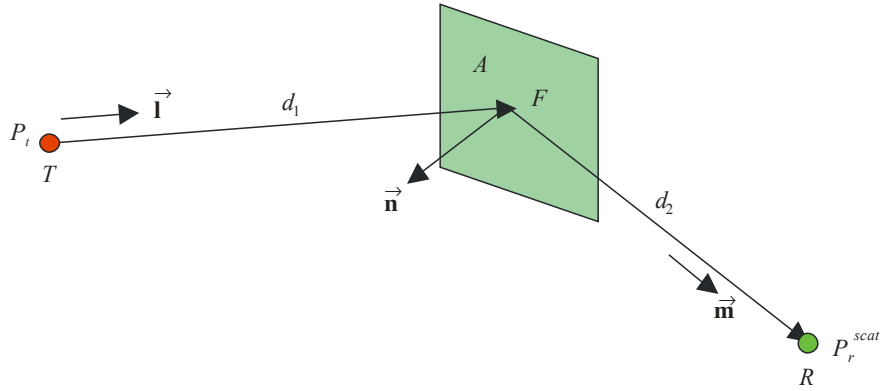
The rough surface scatter model

It is suggested that to minimize computational overhead the simple model given here be used. The model is a scalar model for the incoherent scatter from a rough surface. That is, it only considers scattered power and ignores phase and polarization effects.

Geometry

Consider a rough surface facet F of area A . Let T and R be a transmitter and receiver. $\vec{i}$ and $\vec{m}$ are unit vectors in the directions TF and FR and n is the normal to the facet, Fig. 2.

FIGURE 2
Reflection geometry



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P_t and P_r^{scat} are the transmitted and received, scatter powers at T and R respectively and, without loss of generality, we assume omnidirectional antennas at T and R .

Propagation from T to F

Assuming free-space propagation, the power flux-density (pfd) S (W/m²) at distance d_1 from T is:

$$S = \frac{4\pi}{\lambda^2} \left(\frac{\lambda}{4\pi d_1} \right)^2 P_t \quad (1)$$

where λ is the wavelength. The power P_{fr} impinging on F is then:

$$P_{fr} = SA |\vec{I} \cdot \vec{n}| \quad (2)$$

This result assumes that any dimension of $A \ll d$ so that the pfd is constant across the facet. This is not a strong constraint: in principle the facet A may be taken as small as necessary to make this true. However, in this model it is assumed that F is in fact a whole building face (or at least the illuminated portion of a building face), and it is assumed that this constraint is satisfied. The reference point for the scatter is the centre of the facet.

Model of rough surface scatter

The model is one used for rendering diffuse scatter in computer graphics. It assumes that the incoherent power scattered by the rough surface F is Lambertian. That is, the power is re-radiated in all directions (in the half plane) with an intensity that varies as $\cos \theta$ where θ is the angle of radiation to the normal. This variation exactly cancels the $1/\cos \theta$ dependence of the emitted pfd (due to the $|\vec{m} \cdot \vec{n}|$ projection term) giving omnidirectional radiation with equal gain in all directions. This corresponds to what is observed in practice for optical scatter. The incoherent power emitted by F is given by:

$$P_{ft} = 2\rho_{nonspec} P_{fr} \quad (3)$$

The factor 2 accounts for the fact all the power is emitted into a hemisphere. $\rho_{nonspec}$ accounts for the fraction of the coherent power impinging on F that is re-emitted as non-specular scatter.

Propagation from F to R

Assuming free-space propagation and an omnidirectional antenna, the received scatter power at R is:

$$P_r^{scat} = \left(\frac{\lambda}{4\pi d_2} \right)^2 P_{ft} \quad (4)$$

Full link budget

Combining equations (1) and (2) gives:

$$P_r^{scat} = 2\rho_{nonspec} \frac{4\pi A |\vec{\mathbf{i}} \cdot \vec{\mathbf{n}}|}{\lambda^2} \left(\frac{\lambda}{4\pi d_1} \right)^2 \left(\frac{\lambda}{4\pi d_2} \right)^2 P_t \quad (5)$$

The $(\lambda/4\pi d)^2$ terms are the free-space propagation terms, and can in general be replaced by the actual propagation terms. Antenna gain patterns at T and R can also be included. The only assumption required is that of plane wave incidence at F .

Scatter loss

It may be useful to calculate the incoherent, rough surface, scatter “loss”. This is the additional path loss incurred by the scatter over and above the path loss experienced if the facet were a perfect mirror, that is, a specular reflection with a reflection coefficient of 1. To do this we need to assume free-space propagation on paths TF and FR . The received power at R from a transmitter at T under the perfect reflection assumption, P_r^{LoS} is:

$$P_r^{LoS} = \left(\frac{\lambda}{4\pi(d_1 + d_2)} \right)^2 P_t \quad (6)$$

The scatter loss L_{scat} is then (defined so that $L_{scat} > 1$ for a loss):

$$\frac{1}{L_{scat}} = \frac{P_r^{scat}}{P_r^{LoS}} = \frac{|\vec{\mathbf{i}} \cdot \vec{\mathbf{n}}|}{2\pi} \rho_{nonspec} \frac{(d_1 + d_2)^2 A}{d_1^2 d_2^2} \quad (7)$$

All the terms in this expression are strictly < 1 apart from the last term, which can become > 1 if A is too large compared to d_1 and d_2 . However as noted above, the model is only valid if any dimension of $A \ll d_1$ so an implementation of equation (7) should enforce the condition:

$$\frac{(d_1 + d_2)^2 A}{d_1^2 d_2^2} \leq 1 \quad (8)$$

This will only be violated for transmitter and receiver positions that are extremely close to F .

Equation (7) shows that the non-specular scatter loss increases rapidly as the reception point moves away from the scatter surface. As $d_1 \rightarrow \infty$, the loss (in decibels) $\rightarrow 10 \log(d_2^2 / A)$. So for a building face of 100 m^2 the loss due to this term alone is 20 dB at 100 m and 40 dB at 1 km distance from the building.

Definition of $\rho_{nonspec}$

Defining ρ_{spec} and ρ_{trans} as the fraction of the coherent power impinging on F that is reflected as specular (coherent) reflection and transmitted through the facet, respectively, a consistent model of the complete scatter process might be expected to conserve energy, giving:

$$\rho_{spec} + \rho_{trans} + \rho_{nonspec} = 1 \quad (9)$$

Unfortunately, our semi-empirical model is not consistent, and different assumptions are made for each mechanism:

- ρ_{spec} : the most theoretically based model is that for specular scatter. For a smooth facet, the reflected power is determined by the Fresnel reflection coefficients (which depend on the specular reflection angle, and the electrical properties of the facets). However there is no simple extension for *rough* surface scattering, and the model uses a semi-empirical term that modifies (reduces) the smooth surface Fresnel reflection coefficient. It is proposed that ρ_{spec} is defined as the power reduction factor due to the rough surface effect alone; that is, it does not take account of reflected power variation due to the Fresnel coefficient variation. The latter depends on the reflection angle and polarization, and therefore so would the non-specular scattered power; this would be incompatible with the Lambertian assumption.
- ρ_{trans} : in principle the transmitted component can also be calculated from Fresnel theory for a smooth surface, single interface. However, in practice, the situation is too complicated to model (rough surface, multiple interfaces and reflections) and an experimentally determined, empirical value for ρ_{trans} should be used.

In principle each ρ must satisfy the condition $0 \leq \rho \leq 1$. There is no reason to believe that equation (9) will be satisfied, and if used to derive $\rho_{nonspec}$ from ρ_{spec} and ρ_{trans} , it is possible for $\rho_{nonspec}$ to become negative which is unphysical. It is proposed therefore that the non-specular fraction is derived directly from the specular fraction, ignoring the transmitted component:

$$\rho_{nonspec} = 1 - \rho_{spec} \quad (10)$$

In practice ρ_{trans} is likely to be quite small (e.g. 10 dB building penetration loss implies $\rho_{trans} = 0.1$).

Calculation of ρ_{spec}

ρ_{spec} is the *power* reduction factor applied to the specular reflection coefficient to account for the effect of surface roughness on specular reflection. It is:

$$\rho_{spec} = \rho_s^2 \quad (11)$$

When calculating the specular reflection coefficient, the effective reflection coefficient R is obtained by multiplying the Fresnel coefficient R_F by ρ_s :

$$R = \rho_s R_F \quad (12)$$

ρ_s can be calculated from:

$$\rho_s = \max\left[\exp\left(-\frac{1}{2}g^2\right), 0.15\right] \quad (13)$$

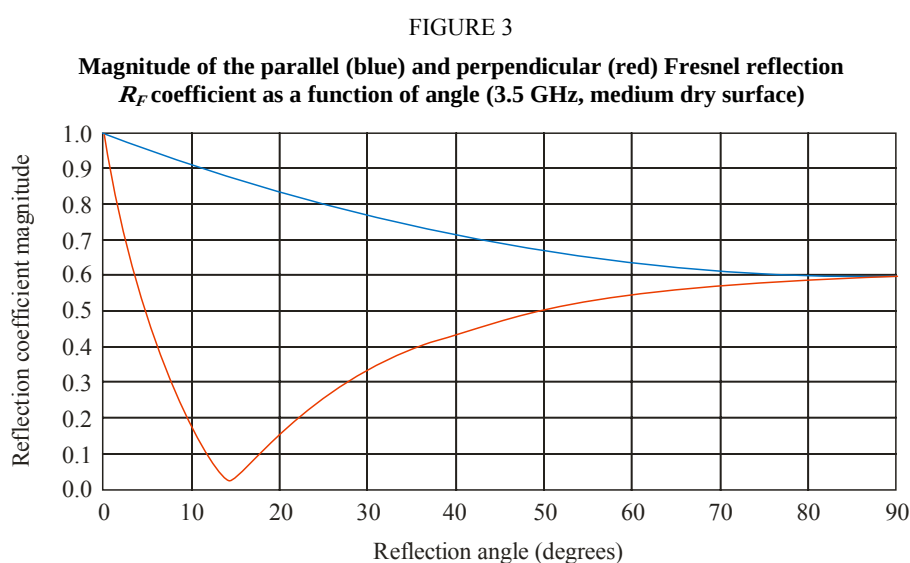
where:

$$g = \frac{4\pi\sigma}{\lambda} \cos \varphi \quad (14)$$

σ is the standard deviation of the surface roughness height about the local mean within the first Fresnel zone, and φ is the angle of incidence to the surface normal. The 0.15 cut-off in equation (13) is to prevent ρ_s becoming too small. (The exponential term tends to underestimate the scatter for very rough surfaces.)

The calculation of the specular reflection coefficient in equation (13) is complicated. The Fresnel coefficient depends on angle, electrical constants and *polarization*. The dependence on polarization means that, in general, both the parallel and perpendicular Fresnel reflection coefficients need to be calculated, and the ray path geometry needs to take account of polarization rotation when calculating the signal at the receiver.

Given the empirical nature of the model, if the modelling is only concerned with signal powers (and can ignore phase) a simplification may be made through calculating all specular reflections based on only the parallel Fresnel coefficient. The magnitude of the coefficient when the electric vector lies in the plane of the incident and reflected rays (blue or upper curve, in Fig. 3) is always numerically greater than the coefficient when the electric is normal to the plane (in red or lower curve). In a 3-dimensional database, there will generally be a mixing of the two polarization components, and the parallel component will tend to mask out the “null” in the perpendicular component.



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Calculation of ρ_{trans}

ρ_{trans} is the fraction of the incident power transmitted through the wall. In this application, it is assumed that the value of ρ_{trans} is a constant independent of the transmission angle relative to the facet and that the facet does not change the angle of the ray as it passes through the facet.

Points to note

- 1 The rough surface scatter loss is given by equation (10) with the non-specular power fraction defined via equations (11), (13) and (14).

- 2 L_{scat} does not depend explicitly on λ , the only frequency dependence being via ρ_{nonpec} . This is as expected – this is a scalar power model, and the Lambertian source model is independent of frequency.
- 3 A model that correctly represents phase and polarization would be much more complex and incompatible with an incoherent scatter model. More importantly it would require detailed knowledge of the form of the surface roughness that is never likely to be available. (This might be possible for a “slightly” rough surface, using a perturbation approach, but such a coherent scatter model would be better dealt with within the framework of a modified specular reflection model.)
- 4 A consequence of point 3 is that this scatter model is really only useful for modelling *interference* since interference powers are assumed to add incoherently. For the wanted signal this result can be used to estimate the delay spread. For the summation needed to get the total signal power, a more detailed consideration of phase (or equivalently, differential path lengths) is necessary.
- 5 The non-specular scatter model does not satisfy reciprocity. In fact it *almost* does, but the inclusion of the $|\vec{l} \cdot \vec{n}|$ term without a corresponding $|\vec{m} \cdot \vec{n}|$ term destroys the symmetry. By choosing a scatter source model other than Lambertian it could be possible to repair this. However, the model is semi-empirical in any case, and reciprocity is not to be expected with the simple assumptions made.

2.1.3 Transmission through buildings

Measurements reported in Recommendation ITU-R P.1411 and (reported measurements references) show that signal penetration through buildings over the lower end of the frequency range may become a significant propagation mechanism (additional loss of 20-40 dB) when diffraction loss around or over the building is large. Similarly to reflection attenuation coefficients these losses will be related to building materials, and radio frequency as well as the buildings internal structure (internal walls). The loss could either be modelled as a series of wall losses (where sufficient data is available), or as loss per metre through the building. Where more than one building blocks the direct path it may be best to ignore this mechanism since then combinations of diffracted, reflected and through building paths should also be considered.

2.1.4 Statistical model

For a given transmitter (Tx) and receiver (Rx) position, the probability that a LoS ray exists between them is given by combining the probabilities that each building lying in the propagation path is below the height of the ray joining the transmitter and receiver at the point where the ray crosses the building. Figure 1 shows the geometry of the situation and defines the terms used in equation (15). This model assumes that the terrain is flat or of constant slope over the area of interest.

The height of the ray at the obstruction point, h_{LoS} , is given by:

$$h_{LoS} = h_{tx} - \frac{r_{LoS}(h_{tx} - h_{rx})}{r_{rx}} \quad (15)$$

where:

- h_{tx} : height above ground of the transmitter
- h_{rx} : height of the receiver at the distance r_{rx}
- r_{LoS} : distance from the transmitter to the obstacle.

If it is assumed that, on average, buildings are evenly spaced, the number of buildings lying between two points can be estimated. The probability that a LoS ray exists is:

$$P(LoS) = \prod_{b=1}^{b_r} P(\text{building_height} < h_{LoS}) \quad (16)$$

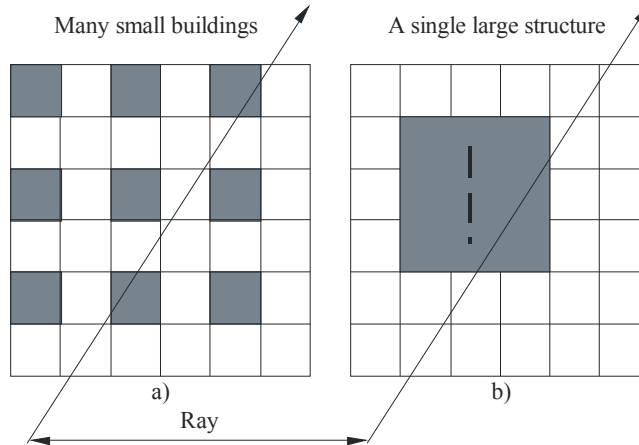
where b_r is the number of buildings crossed.

For this simple model, three parameters are required:

- α : the ratio of land area covered by buildings to total land area (dimensionless);
- β : the mean number of buildings per unit area (buildings/km²);
- γ : a variable determining the building height distribution.

For the proposed Rayleigh distribution, the variable γ equates to the most probable (mode) building height. The reason for the distinction between α and β is illustrated in Fig. 4. Both Figs. 4a) and 4b) have the same ground area covered and hence the same value of α , but more ray interactions are expected in Fig. 4a) than in Fig. 4b). α alone does not distinguish between the two patterns shown in Fig. 4. If the buildings are of a similar height in both Figs. 4a) and 4b), the probability of clearing many small buildings will be significantly less than that of clearing one large building.

FIGURE 4
Two scenarios with the same area covered but different number of ray interactions



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For suburban to high-rise locations α will range from 0.1 to 0.8 and β from 750 to 100 respectively.

The Rayleigh probability distribution $P(h)$ of the height h defines the parameter γ :

$$P(h) = \frac{h^2}{\gamma^2} e^{-\frac{h^2}{2\gamma^2}} \quad (17)$$

2.1.5 Algorithm and computation

Given α , β and γ the LoS coverage is computed as follows:

A ray of length 1 km would pass over $\sqrt{\beta}$ buildings if they were arranged on a regular grid. As only a fraction α of land is covered, the expected number of buildings passed per km is given by:

$$b_1 = \sqrt{\alpha \beta} \quad (18)$$