RECOMMENDATION ITU-R P.1411-3

Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz

(Question ITU-R 211/3)

(1999-2001-2003-2005)

The ITU Radiocommunication Assembly,

considering

a) that many new short-range (operating range less than 1 km) mobile and personal communication applications are being developed;

b) that there is a high demand for radio local area networks (RLANs) and wireless local loop systems;

c) that short-range systems using very low power have many advantages for providing services in the mobile and wireless local loop environment;

d) that knowledge of the propagation characteristics and the interference arising from multiple users in the same area is critical to the efficient design of systems;

e) that there is a need both for general (i.e. site-independent) models and advice for initial system planning and interference assessment, and for deterministic (or site-specific) models for some detailed evaluations,

noting

a) that Recommendation ITU-R P.1238 provides guidance on indoor propagation over the frequency range 900 MHz to 100 GHz, and should be consulted for those situations where both indoor and outdoor conditions exist;

b) that Recommendation ITU-R P.1546 provides guidance on propagation for systems that operate over distances of 1 km and greater, and over the frequency range 30 MHz to 3 GHz,

recommends

1 that the information and methods in Annex 1 be adopted for the assessment of the propagation characteristics of short-range outdoor radio systems between 300 MHz and 100 GHz where applicable.

Annex 1

1 Introduction

Propagation over paths of length less than 1 km is affected primarily by buildings and trees, rather than by variations in ground elevation. The effect of buildings is predominant, since most short-path radio links are found in urban and suburban areas. The mobile terminal is most likely to be held by a pedestrian or located in a vehicle.

This Recommendation defines categories for short propagation paths, and provides methods for estimating path loss and delay spread over these paths.

2 Physical operating environments and definition of cell types

Environments described in this Recommendation are categorized solely from the radio propagation perspective. Radiowave propagation is influenced by the environment, i.e. building structures and heights, the usage of the mobile terminal (pedestrian/vehicular) and the positions of the antennas. Four different environments are identified, considered to be the most typical. Hilly areas, for example, are not considered, as they are less typical in metropolitan areas. Table 1 lists the four environments. Recognizing that there is a wide variety of environments within each category, it is not intended to model every possible case but to give propagation models that are representative of environments frequently encountered.

TABLE 1

Physical operating environments – Propagation impairments

Environment	Description and propagation impairments of concern
Urban high-rise	– Urban canyon, characterized by streets lined with tall buildings of several floors each – Building height makes significant contributions from propagation over roof-tops unlikely – Rows of tall buildings provide the possibility of long path delays – Large numbers of moving vehicles in the area act as reflectors adding Doppler shift to the reflected waves
Urban/suburban low-rise	– Typified by wide streets – Building heights are generally less than three stories making diffraction over roof-top likely – Reflections and shadowing from moving vehicles can sometimes occur – Primary effects are long delays and small Doppler shifts
Residential	– Single and double storey dwellings – Roads are generally two lanes wide with cars parked along sides – Heavy to light foliage possible – Motor traffic usually light
Rural	– Small houses surrounded by large gardens – Influence of terrain height (topography) – Heavy to light foliage possible – Motor traffic sometimes high

For each of the four different environments two possible scenarios for the mobile are considered. Therefore the users are subdivided into pedestrian and vehicular users. For these two applications the velocity of the mobile is quite different yielding different Doppler shifts. Table 2 shows typical velocities for these scenarios.

TABLE 2

Physical operating environments – Typical mobile velocity

Environment	Velocity for pedestrian users (m/s)	Velocity for vehicular users
Urban high-rise	1.5	Typical downtown speeds around 50 km/h (14 m/s)
Urban/suburban low-rise	1.5	Around 50 km/h (14 m/s) Expressways up to 100 km/h (28 m/s)
Residential	1.5	Around 40 km/h (11 m/s)
Rural	1.5	80-100 km/h (22-28 m/s)

The type of propagation mechanism that dominates depends also on the height of the base station antenna relative to the surrounding buildings. Table 3 lists the typical cell types relevant for outdoor short-path propagation.

TABLE 3

Definition of cell types

Cell type	Cell radius	Typical position of base station antenna
Small macro-cell	0.5 to 3 km	Outdoor; mounted above average roof-top level, heights of some surrounding buildings may be above base station antenna height
Micro-cell	100 to 500 m	Outdoor; mounted below average roof-top level
Pico-cell	Up to 100 m	Indoor or outdoor (mounted below roof-top level)

(Note that although the "small macro-cell" category is given an upper limit of 3 km, this Recommendation is intended for distances up to 1 km.)

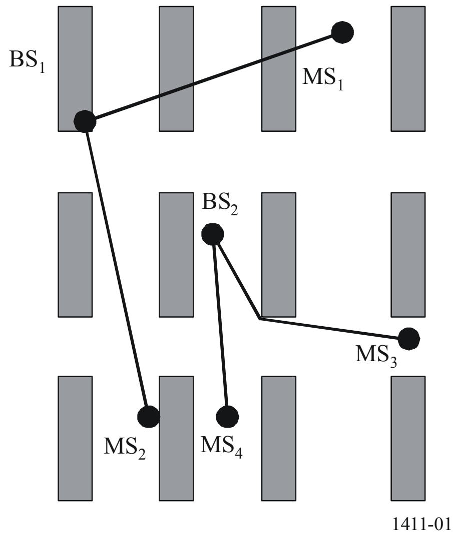
3 Path categories

3.1 Definition of propagation situations

Four situations of base station (BS) and mobile station (MS) geometries are depicted in Fig. 1. Base station BS_1 is mounted above roof-top level. The corresponding cell is a small macro-cell. Propagation from this base station is mainly over the roof-tops. Base station BS_2 is mounted below roof-top level and defines a micro- or pico-cellular environment. In these cell types, propagation is mainly within street canyons. For mobile-to-mobile links, both ends of the link can be assumed to be below roof-top level, and the models relating to BS_2 may be used.

FIGURE 1

Typical propagation situations in urban areas

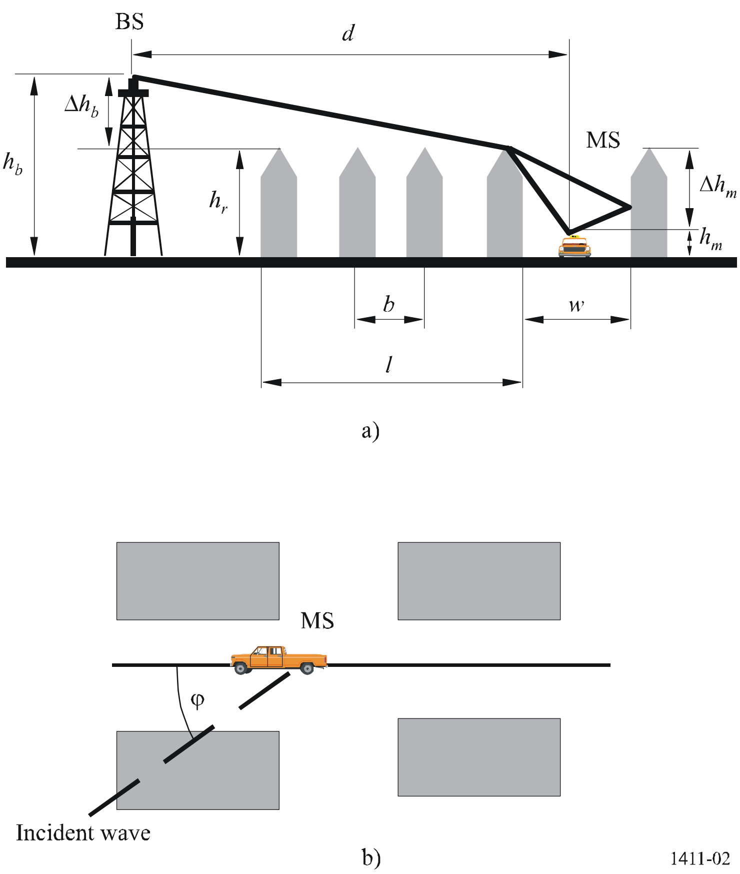


3.1.1 Propagation over rooftops, non-line-of-sight (NLoS)

The typical NLoS case (link BS_1-MS_1 in Fig. 1) is described by Fig. 2. In the following, this case is called NLoS1.

FIGURE 2

Definition of parameters for the NLoS1 case



The relevant parameters for this situation are:

h_r: average height of buildings (m)

w: street width (m)

b: average building separation (m)

φ: street orientation with respect to the direct path (degrees)

h_b: BS antenna height (m)

h_m: MS antenna height (m)

l: length of the path covered by buildings (m)

d: distance from BS to MS.

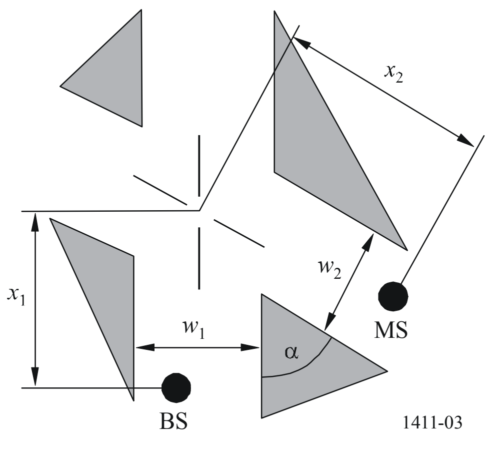
The NLoS1 case frequently occurs in residential/rural environments for all cell-types and is predominant for small macro-cells in urban/suburban low-rise environments. The parameters h_r, b and l can be derived from building data along the line between the antennas. However, the determination of w and φ requires a two-dimensional analysis of the area around the mobile. Note that l is not necessarily normal to the building orientation.

3.1.2 Propagation along street canyons, NLoS

Figure 3 depicts the situation for a typical micro-cellular NLoS-case (link BS_2-MS_3 in Fig. 1). In the following, this case is called NLoS2.

FIGURE 3

Definition of parameters for the NLoS2 case



The relevant parameters for this situation are:

w_1: street width at the position of the BS (m)

w_2: street width at the position of the MS (m)

x_1: distance BS to street crossing (m)

x_2: distance MS to street crossing (m)

α: is the corner angle (rad).

NLoS2 is the predominant path type in urban high-rise environments for all cell-types and occurs frequently in micro- and pico-cells in urban low-rise environments. The determination of all parameters for the NLoS2 case requires a two-dimensional analysis of the area around the mobile.

3.1.3 Line-of-sight (LoS) paths

The paths BS_1-MS_2 and BS_2-MS_4 in Fig. 1 are examples of LoS situations. The same models can be applied for both types of LoS path.

3.2 Data requirements

For site-specific calculations in urban areas, different types of data can be used. The most accurate information can be derived from high-resolution data where information consists of:

– building structures;

– relative and absolute building heights;

– vegetation information.

Data formats can be both raster and vector. The location accuracy of the vector data should be of the order of 1 to 2 m. The recommended resolution for the raster data is 1 to 10 m. The height accuracy for both data formats should be of the order of 1 to 2 m.

If no high-resolution data are available, low-resolution land-use data (50 m resolution) are recommended. Depending on the definition of land-use classes (dense urban, urban, suburban, etc.) the required parameters can be assigned to these land-use classes. These data can be used in conjunction with street vector information in order to extract street orientation angles.

4 Path loss models

For typical scenarios in urban areas some closed-form algorithms can be applied. These propagation models can be used both for site-specific and site-general calculations. The corresponding propagation situations are defined in § 3.1. The type of the model depends also on the frequency range. Different models have to be applied for UHF propagation and for mm-wave propagation. In the UHF frequency range LoS and NLoS situations are considered. In mm-wave propagation LoS is considered only. Additional attenuation by oxygen and hydrometeors has to be considered in the latter frequency range.

4.1 LoS situations within street canyons

UHF propagation

In the UHF frequency range, basic transmission loss, as defined by Recommendation ITU-R P.341, can be characterized by two slopes and a single breakpoint. An approximate lower bound is given by:

$$L_{LoS,l} = L_{bp} + \begin{cases} 20 \log_{10}\left(\dfrac{d}{R_{bp}}\right) & \text{for} \quad d \le R_{bp} \\ 40 \log_{10}\left(\dfrac{d}{R_{bp}}\right) & \text{for} \quad d > R_{bp} \end{cases} \qquad (1)$$

where R_{bp} is the breakpoint distance and is given by:

$$R_{bp} \approx \frac{4 h_b h_m}{\lambda} \qquad (2)$$

where λ is the wavelength (m).

An approximate upper bound is given by:

$$L_{LoS,u} = L_{bp} + 20 + \begin{cases} 25 \log_{10}\left(\dfrac{d}{R_{bp}}\right) & \text{for} \quad d \le R_{bp} \\ \\ 40 \log_{10}\left(\dfrac{d}{R_{bp}}\right) & \text{for} \quad d > R_{bp} \end{cases} \tag{3}$$

L_{bp} is a value for the basic transmission loss at the break point, defined as:

$$L_{bp} = \left| 20 \log_{10}\left(\frac{\lambda^2}{8\pi h_b h_m}\right) \right| \tag{4}$$

SHF propagation up to 15 GHz

At SHF, for path lengths up to about 1 km, road traffic will influence the effective road height and will thus affect the breakpoint distance. This distance, R_{bp}, is estimated by:

$$R_{bp} = 4 \frac{(h_b - h_s)(h_m - h_s)}{\lambda} \tag{5}$$

where h_s is the effective road height due to such objects as vehicles on the road and pedestrians near the roadway. Hence h_s depends on the traffic on the road. The h_s values given in Tables 4 and 5 are derived from daytime and night-time measurements, corresponding to heavy and light traffic conditions, respectively. Heavy traffic corresponds to 10-20% of the roadway covered with vehicles, and 0.2-1% of the footpath occupied by pedestrians. Light traffic was 0.1-0.5% of the roadway and less than 0.001% of the footpath occupied. The roadway was 27 m wide, including 6 m wide footpaths on either side.

TABLE 4

The effective height of the road, h_s (heavy traffic)

Frequency (GHz)	**h_b (m)**	**h_s (m)**	
		$h_m = 2.7$	$h_m = 1.6$
3.35	4	1.3	(2)
	8	1.6	(2)
8.45	4	1.6	(2)
	8	1.6	(2)
15.75	4	1.4	(2)
	8	(1)	(2)

(1) The breakpoint is beyond 1 km.

(2) No breakpoint exists.

TABLE 5

The effective height of the road, h_s (light traffic)

Frequency (GHz)	h_b (m)	h_s (m)	
		$h_m = 2.7$	$h_m = 1.6$
3.35	4	0.59	0.23
	8	(1)	(1)
8.45	4	(2)	0.43
	8	(2)	(1)
15.75	4	(2)	0.74
	8	(2)	(1)

(1) No measurements taken.

(2) The breakpoint is beyond 1 km.

When $h_m > h_s$, the approximate values of the upper and lower bounds of basic transmission loss for the SHF frequency band can be calculated using equations (1) and (3), with L_{bp} given by:

$$L_{bp} = \left| 20 \log_{10} \left\{ \frac{\lambda^2}{8\pi(h_b - h_s)(h_m - h_s)} \right\} \right| \qquad (6)$$

On the other hand, when $h_m \leq h_s$ no breakpoint exists. The area near the BS ($d < R_s$) has a basic propagation loss similar to that of the UHF range, but the area distant from the BS has propagation characteristics in which the attenuation coefficient is cubed. Therefore, the approximate lower bound for $d \geq R_s$ is given by:

$$L_{LoS,l} = L_s + 30 \log_{10} \left(\frac{d}{R_s} \right) \qquad (7)$$

The approximate upper bound for $d \geq R_s$ is given by:

$$L_{LoS,u} = L_s + 20 + 30 \log_{10} \left(\frac{d}{R_s} \right) \qquad (8)$$

The basic propagation loss L_s is defined as:

$$L_s = \left| 20 \log_{10} \left(\frac{\lambda}{2\pi R_s} \right) \right| \qquad (9)$$

R_s in equations (7) to (9) has been experimentally determined to be 20 m.

Millimetre-wave propagation

At frequencies above about 10 GHz, the breakpoint distance R_{bp} in equation (2) is far beyond the expected maximum cell radius (500 m). This means that no fourth-power law is expected in this frequency band. Hence the power distance decay-rate will nearly follow the free-space law with a path-loss exponent of about 2.2. Attenuation by atmospheric gases and by rain must also be considered.

Gaseous attenuation can be calculated from Recommendation ITU-R P.676, and rain attenuation from Recommendation ITU-R P.530.

4.2 Models for NLoS situations

NLoS signals can arrive at the BS or MS by diffraction mechanisms or by multipath which may be a combination of diffraction and reflection mechanisms. This section develops models that relate to diffraction mechanisms.

UHF and SHF propagation

Models are defined for the two situations described in § 3.1. The models are valid for:

h_b: 4 to 50 m

h_m: 1 to 3 m

f: 800 to 2 000 MHz for $h_b \leq h_r$

800 to 5 000 MHz for $h_b > h_r$

d: 20 to 5 000 m.

(Note that although the model is valid up to 5 km, this Recommendation is intended for distances only up to 1 km.)

Millimetre-wave propagation

Millimetre-wave signal coverage is considered only for LoS situations because of the large diffraction losses experienced when obstacles cause the propagation path to become NLoS. For NLoS situations, multipath reflections and scattering will be the most likely signal propagation method.

4.2.1 Propagation over roof-tops

The multi-screen diffraction model given below is valid if the roof-tops are all about the same height. Assuming the roof-top heights differ only by an amount less than the first Fresnel-zone radius over a path of length l (Fig. 2), the roof-top height to use in the model is the average roof-top height. If the roof-top heights vary by much more than the first Fresnel-zone radius, a preferred method is to use the highest buildings along the path in a knife-edge diffraction calculation, as described in Recommendation ITU-R P.526, to replace the multi-screen model.

In the model for transmission loss in the NLoS1-case (see Fig. 2) for roof-tops of similar height, the loss between isotropic antennas is expressed as the sum of free-space loss, L_{bf}, the diffraction loss from roof-top to street L_{rts} and the reduction due to multiple screen diffraction past rows of buildings, L_{msd}.

In this model L_{bf} and L_{rts} are independent of the BS antenna height, while L_{msd} is dependent on whether the base station antenna is at, below or above building heights.

$$L_{NLoS1} = \begin{cases} L_{bf} + L_{rts} + L_{msd} & \text{for} \quad L_{rts} + L_{msd} > 0 \\ L_{bf} & \text{for} \quad L_{rts} + L_{msd} \leq 0 \end{cases} \tag{10}$$

The free-space loss is given by:

$$L_{bf} = 32.4 + 20 \log_{10} (d / 1000) + 20 \log_{10} (f) \tag{11}$$

where:

d: path length (m)

f: frequency (MHz).

The term L_{rts} describes the coupling of the wave propagating along the multiple-screen path into the street where the mobile station is located. It takes into account the width of the street and its orientation.

$$L_{rts} = -8.2 - 10 \log_{10} (w) + 10 \log_{10} (f) + 20 \log_{10} (\Delta h_m) + L_{ori} \qquad (12)$$

$$L_{ori} = \begin{cases} -10 + 0.354\varphi & \text{for} \quad 0° \le \varphi < 35° \\ 2.5 + 0.075(\varphi - 35) & \text{for} \quad 35° \le \varphi < 55° \\ 4.0 - 0.114(\varphi - 55) & \text{for} \quad 55° \le \varphi \le 90° \end{cases} \qquad (13)$$

where:

$$\Delta h_m = h_r - h_m \qquad (14)$$

L_{ori} is the street orientation correction factor, which takes into account the effect of roof-top-to-street diffraction into streets that are not perpendicular to the direction of propagation (see Fig. 2b)).

The multiple screen diffraction loss from the BS due to propagation past rows of buildings depends on the BS antenna height relative to the building heights and on the incidence angle. A criterion for grazing incidence is the "settled field distance", d_s:

$$d_s = \frac{\lambda d^2}{\Delta h_b^2} \qquad (15)$$

where (see Fig. 2a)):

$$\Delta h_b = h_b - h_r \qquad (16)$$

For the calculation of L_{msd}, d_s is compared to the distance l over which the buildings extend.

Calculation of L_{msd} *for* $l > d_s$

(Note this calculation becomes more accurate when $l \gg d_s$.)

$$L_{msd} = L_{bsh} + k_a + k_d \log_{10} (d / 1000) + k_f \log_{10} (f) - 9 \log_{10} (b) \qquad (17)$$

where:

$$L_{bsh} = \begin{cases} -18 \log_{10}(1 + \Delta h_b) & \text{for} \quad h_b > h_r \\ 0 & \text{for} \quad h_b \le h_r \end{cases} \qquad (18)$$

is a loss term that depends on the BS height,

$$k_a = \begin{cases} 71.4 & \text{for} \quad h_b > h_r \text{ and } f > 2\,000 \text{ MHz} \\ 54 & \text{for} \quad h_b > h_r \text{ and } f \le 2\,000 \text{ MHz} \\ 54 - 0.8\Delta h_b & \text{for} \quad h_b \le h_r \text{ and } d \ge 500 \text{ m} \\ 54 - 1.6\Delta h_b \, d/1\,000 & \text{for} \quad h_b \le h_r \text{ and } d < 500 \text{ m} \end{cases} \qquad (19)$$

$$k_d = \begin{cases} 18 & \text{for} \quad h_b > h_r \\ 18 - 15\dfrac{\Delta h_b}{h_r} & \text{for} \quad h_b \le h_r \end{cases} \qquad (20)$$

$$k_f = \begin{cases} -8 & \text{for } f > 2000 \text{ MHz} \\ -4 + 0.7(f/925 - 1) & \text{for medium sized city and suburban} \\ & \text{centres with medium tree density and } f \leq 2\ 000 \text{ MHz} \\ -4 + 1.5(f/925 - 1) & \text{for metropolitan centres and } f \leq 2\ 000 \text{ MHz} \end{cases} \tag{21}$$

Calculation of L_{msd} for $l < d_s$

In this case a further distinction has to be made according to the relative heights of the BS and the rooftops.

$$L_{msd} = -10 \log_{10}\left(Q_M^2\right) \tag{22}$$

where:

$$Q_M = \begin{cases} 2.35\left(\dfrac{\Delta h_b}{d}\sqrt{\dfrac{b}{\lambda}}\right)^{0.9} & \text{for } h_b > h_r \\ \dfrac{b}{d} & \text{for } h_b \approx h_r \\ \dfrac{b}{2\pi d}\sqrt{\dfrac{\lambda}{\rho}}\left(\dfrac{1}{\theta} - \dfrac{1}{2\pi + \theta}\right) & \text{for } h_b < h_r \end{cases} \tag{23}$$

and

$$\theta = \arctan\left(\frac{\Delta h_b}{b}\right) \tag{24}$$

$$\rho = \sqrt{\Delta h_b^2 + b^2} \tag{25}$$

4.2.2 Propagation within street canyons

For NLoS2 situations where both antennas are below roof-top level, diffracted and reflected waves at the corners of the street crossings have to be considered (see Fig. 3).

$$L_{NLoS2} = -10\log_{10}\left(10^{-L_r/10} + 10^{-L_d/10}\right) \quad \text{dB} \tag{26}$$

where:

L_r: reflection path loss defined by:

$$L_r = 20 \log_{10}(x_1 + x_2) + x_1 x_2 \frac{f(\alpha)}{w_1 w_2} + 20 \log_{10}\left(\frac{4\pi}{\lambda}\right) \quad \text{dB} \tag{27}$$

where:

$$f(\alpha) = \frac{3.86}{\alpha^{3.5}} \quad \text{dB} \tag{28}$$

where $0.6 < \alpha$ [rad] $< \pi$.

L_d: diffraction path loss defined by:

$$L_d = 10 \log_{10}\left[x_1 x_2 (x_1 + x_2)\right] + 2D_a - 0.1\left(90 - \alpha\frac{180}{\pi}\right) + 20 \log_{10}\left(\frac{4\pi}{\lambda}\right) \quad \text{dB} \tag{29}$$

$$D_a = \left(\frac{40}{2\pi}\right)\left[\arctan\left(\frac{x_2}{w_2}\right) + \arctan\left(\frac{x_1}{w_1}\right) - \frac{\pi}{2}\right] \quad \text{dB} \tag{30}$$

4.3 Default parameters for site-general calculations

If the data on the structure of buildings and roads are unknown (site-general situations), the following default values are recommended:

h_r = 3 × (number of floors) + roof-height (m)

roof-height = 3 m for pitched roofs
= 0 m for flat roofs

w = $b/2$
b = 20 to 50 m
φ = 90°.

4.4 Influence of vegetation

The effects of propagation through vegetation (primarily trees) are important for outdoor short-path predictions. Two major propagation mechanisms can be identified:

– propagation through (not around or over) trees;

– propagation over trees.

The first mechanism predominates for geometries in which both antennas are below the tree tops and the distance through the trees is small, while the latter predominates for geometries in which one antenna is elevated above the tree tops. The attenuation is strongly affected by multipath scattering initiated by diffraction of the signal energy both over and through the tree structures. For propagation through trees, the specific attenuation in vegetation can be found in Recommendation ITU-R P.833. In situations where the propagation is over trees, diffraction is the major propagation mode over the edges of the trees closest to the low antenna. This propagation mode can be modelled most simply by using an ideal knife-edge diffraction model (see Recommendation ITU-R P.526), although the knife-edge model may underestimate the field strength, because it neglects multiple scattering by tree-tops, a mechanism that may be modelled by radiative transfer theory.

5 Building entry loss

Building entry loss is the excess loss due to the presence of a building wall (including windows and other features). It is defined as the difference between the signal levels outside and inside the building at the same height. Account must also be taken of the incident angle. (When the path length is less than about 10 m, the difference in free space loss due to the change in path length for the two measurements should be taken into account in determining the building entry loss. For antenna locations close to the wall, it may also be necessary to consider near-field effects.) Additional losses will occur for penetration within the building; advice is given in Recommendation ITU-R P.1238. It is believed that, typically, the dominant propagation mode is one in which signals enter a building approximately horizontally through the wall surface (including windows), and that for a building of uniform construction the building entry loss is independent of height.

Building entry loss should be considered when evaluating the radio coverage from an outdoor system to an indoor terminal. It is also important for considering interference problems between outdoor systems and indoor systems.

The experimental results shown in Table 6 were obtained at 5.2 GHz through an external building wall made of brick and concrete with glass windows. The wall thickness was 60 cm and the window-to-wall ratio was about 2:1.

TABLE 6

Example of building entry loss

Frequency	**Residential**		**Office**		**Commercial**	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
5.2 GHz			12 dB	5 dB		

Table 7 shows the results of measurements at 5.2 GHz through an external wall made of stone blocks, at incident angles from 0° to 75°. The wall was 400 mm thick, with two layers of 100 mm thick blocks and loose fill between. Particularly at larger incident angles, the loss due to the wall was extremely sensitive to the position of the receiver, as evidenced by the large standard deviation.

TABLE 7

Loss due to stone block wall at various incident angles

Incident angle (degrees)	0	15	30	45	60	75
Loss due to wall (dB)	28	32	32	38	45	50
Standard deviation (dB)	4	3	3	5	6	5

Additional information on building entry loss, intended primarily for satellite systems, can be found in Recommendation ITU-R P.679 and may be appropriate for the evaluation of building entry for terrestrial systems.

6 Multipath models

A description of multipath propagation and definition of terms are provided in Recommendation ITU-R P.1407.

6.1 Multipath models for street canyon environments

Characteristics of multipath delay spread for the LoS case in an urban high-rise environment for micro-cells and pico-cells (as defined in Table 3) have been developed based on measured data at frequencies from 2.5 to 15.75 GHz at distances from 50 to 400 m. The r.m.s. delay spread S at distance of d m follows a normal distribution with the mean value given by:

$$a_s = C_a d^{\gamma_a} \qquad \text{ns} \tag{31}$$

and the standard deviation given by:

$$\sigma_s = C_\sigma d^{\gamma_\sigma} \qquad \text{ns} \tag{32}$$

where C_a, γ_a, C_σ and γ_σ depend on the antenna height and propagation environment. Table 8 lists some typical values of the coefficients for distances of 50-400 m based on measurements made in urban and residential areas.

TABLE 8

Typical coefficients for the distance characteristics of r.m.s. delay spread

<table>
<tr><th colspan="4">Measurement conditions</th><th colspan="2">a_s</th><th colspan="2">σ_s</th></tr>
<tr><th>Area</th><th>f (GHz)</th><th>h_b (m)</th><th>h_m (m)</th><th>C_a</th><th>γ_a</th><th>C_σ</th><th>γ_σ</th></tr>
<tr><td rowspan="4">Urban</td><td>2.5</td><td>6.0</td><td>3.0</td><td>55</td><td>0.27</td><td>12</td><td>0.32</td></tr>
<tr><td rowspan="2">3.35-15.75</td><td rowspan="3">4.0</td><td>2.7</td><td>23</td><td>0.26</td><td>5.5</td><td>0.35</td></tr>
<tr><td>1.6</td><td rowspan="2">10</td><td rowspan="2">0.51</td><td rowspan="2">6.1</td><td rowspan="2">0.39</td></tr>
<tr><td>3.35-8.45</td><td>0.5</td></tr>
<tr><td rowspan="2">Residential</td><td>3.35</td><td rowspan="2">4.0</td><td>2.7</td><td>2.1</td><td>0.53</td><td>0.54</td><td>0.77</td></tr>
<tr><td>3.35-15.75</td><td>1.6</td><td>5.9</td><td>0.32</td><td>2.0</td><td>0.48</td></tr>
</table>

From the measured data at 2.5 GHz, the average shape of the delay profile was found to be:

$$P(t) = P_0 + 50\left(e^{-t/\tau} - 1\right) \quad \text{dB} \tag{33}$$

where:

P_0: peak power (dB)

τ: decay factor

and t is in ns.

From the measured data, for an r.m.s. delay spread S, τ can be estimated as:

$$\tau = 4\,S + 266 \quad \text{ns} \tag{34}$$

A linear relationship between τ and S is only valid for the LoS case.

From the same measurement set, the instantaneous properties of the delay profile have also been characterized. The energy arriving in the first 40 ns has a Rician distribution with a K-factor of about 6 to 9 dB, while the energy arriving later has a Rayleigh or Rician distribution with a K-factor of up to about 3 dB. (See Recommendation ITU-R P.1057 for definitions of probability distributions.)

6.2 Multipath models for over-rooftops propagation environments

Characteristics of multipath delay spread for both LoS and NLoS case in an urban high-rise environment for small macro-cells (as defined in Table 3) have been developed based on measured data at 1 920-1 980 MHz and 2 110-2 170 MHz using omnidirectional antennas. The median r.m.s. delay spread S in this environment is given by:

$$S_u = \exp(A \cdot L + B) \quad \text{ns} \tag{35}$$

where $A = 0.038$, $B = 2.3$, and L is path loss (dB).

From the same measurement set, values of r.m.s. delay spread at different frequency bands (190 MHz apart) were compared at each location. More than 10% of locations showed larger than 300 ns differences in r.m.s. delay spread with 25 dB threshold, and larger than 2 μs differences in delay interval using 15 dB threshold.

The distributions of the multipath delay characteristics for the 5.2 GHz band in a suburban environment with a BS antenna height of 20 m, and MS antenna height of 2.8 m were derived from measurements. Table 9 lists the measured r.m.s. delay spread for the 5.2 GHz band for cases where the cumulative probability is 50% and 95%.

TABLE 9

Typical r.m.s. delay spread values*

Measurement conditions					r.m.s. delay spread (ns)	
Area	**Frequency (GHz)**	**Antenna height**		**Range (m)**	**50%**	**95%**
		h_{BS} **(m)**	h_r **(m)**			
Suburban	5.2	20	2.8	100-1 000	189	577

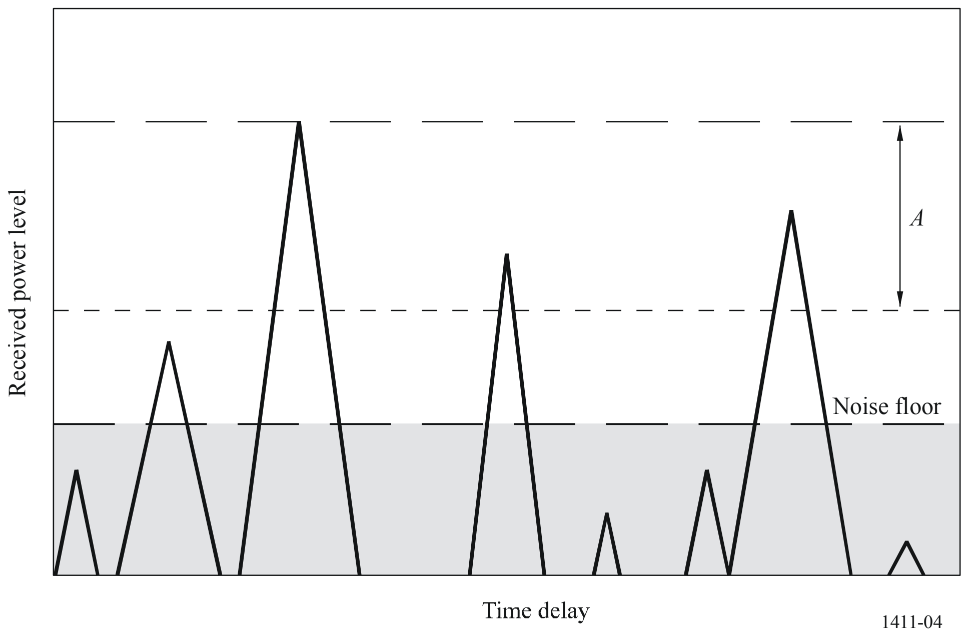
* Threshold value of 30 dB was used for r.m.s. delay spread calculation.

7 Number of signal components

For the design of high data rate systems with multipath separation and synthesis techniques, it is important to estimate the number of signal components (that is, a dominant component plus multipath components) arriving at the receiver. The number of signal components can be represented from the delay profile as the number of peaks whose amplitudes are within *A* dB of the highest peak and above the noise floor, as shown in Fig. 4.

FIGURE 4

Definition for the determination of the number of peaks



Tables 10 to 12 show the results of measurements for three different scenarios (a low BS antenna in an urban area; a high BS antenna in an urban area; a low BS antenna in a residential area). The temporal resolution in the measurements was 20 ns. Table 13 shows the results of measurements for a high BS antenna in a suburban environment. The temporal resolution for this measurement was 50 ns. These Tables list the maximum number of signal components which have been observed at 80% and 95% of locations in each measurement section.

TABLE 10

Maximum number of signal components (for measurements using a low BS antenna in an urban area)

Frequency (GHz)	**Antenna height (m)**		**Range (m)**	**Maximum number of signal components**					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.35	4	1.6	0-200	2	3	2	4	5	6
			0-1 000	2	3	2	4	5	9
8.45	4	1.6	0-200	1	3	2	3	4	6
			0-1 000	1	2	2	4	4	8
15.75	4	1.6	0-200	1	3	2	3	4	5
			0-1 000	2	3	2	4	6	10

TABLE 11

Maximum number of signal components (for measurements using a high BS antenna in an urban area)

Frequency (GHz)	**Antenna height (m)**		**Range (m)**	**Maximum number of signal components**					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.35	55	2.7	150-590	2	2	2	3	3	13
8.45	55	2.7	150-590	2	2	2	3	3	12

TABLE 12

Maximum number of signal components (for measurements using a low BS antenna in a residential area)

Frequency (GHz)	**Antenna height (m)**		**Range (m)**	**Maximum number of signal components**					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.35	4	2.7	0-480	2	2	2	2	2	3

TABLE 13

Maximum number of signal components (for measurements using a high BS antenna in a suburban area)

Frequency (GHz)	Antenna height (m)		Range (m)	Maximum number of signal components					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.67	40	2.7	0-5 000	1	2	1	3	3	5

8 Polarization characteristics

Cross-polarization discrimination (XPD), as defined in Recommendation ITU-R P.310, differs between LoS and NLoS areas in an SHF micro cellular environment. Measurements indicate a median XPD of 13 dB for LoS paths and 8 dB for NLoS paths, and a standard deviation of 3 dB for LoS paths and 2 dB for NLoS paths at SHF. These median values are compatible with the UHF values for open and urban areas, respectively, in Recommendation ITU-R P.1406.

9 Characteristics of direction of arrival

The r.m.s. angular spread as defined in Recommendation ITU-R P.1407 in the azimuthal direction in a microcell or picocell environment in an urban area was obtained from the measurement made at a frequency of 8.45 GHz. The receiving base station had a parabolic antenna with a half-power beamwidth of 4°. The antenna heights of the transmitting mobile station and the receiving base station were 2.7 m and 4.4 m, respectively.

In the LoS situation, the r.m.s. angular spread has an average value of 30° (standard deviation of 11°). In the NLoS situation, the r.m.s. angular spread has an average value of 41° (standard deviation of 18°).

10 Fading characteristics

The fading depth, which is defined as the difference between the 50% value and the 1% value in the cumulative probability of received signal levels, is expressed as a function of the product ($2\Delta f \Delta L_{max}$ MHz·m) of the received bandwidth $2\Delta f$ MHz and the maximum difference in propagation path lengths ΔL_{max} m as shown in Fig. 5. ΔL_{max} is the maximum difference in propagation path lengths between components whose level is larger than the threshold, which is 20 dB lower than the highest level of the indirect waves as shown in Fig. 6. In this Figure, a in decibels is the power ratio of the direct to the sum of indirect waves, and $a = -\infty$ dB represents a NLoS situation. When $2\Delta f \Delta L_{max}$ is less than 10 MHz·m, the received signal levels in LoS and NLoS situations follow Rayleigh and Nakagami-Rice distributions, corresponding to a narrow-band fading region. When it is larger than 10 MHz·m, it corresponds to a wideband fading region, where the fading depth becomes smaller and the received signal levels follow neither Rayleigh nor Nakagami-Rice distributions.

FIGURE 5

Relationship between fading depth and $2\Delta f\Delta L_{max}$

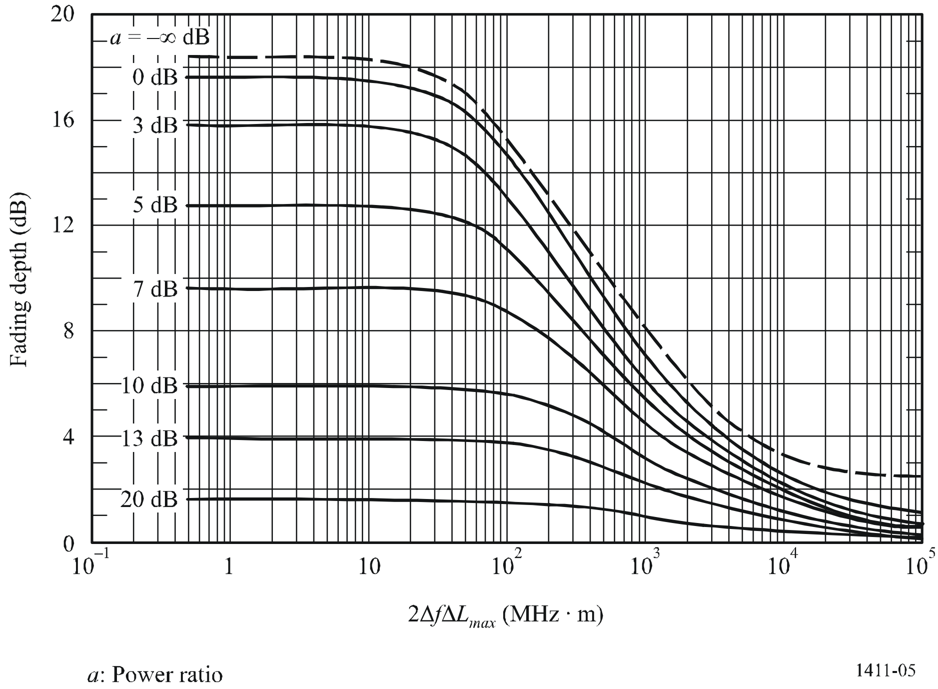


FIGURE 6

Model for calculating ΔL_{max}