



**Recommendation ITU-R P.1411-6**  
(02/2012)

**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**

**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.1411-6

**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)

(1999-2001-2003-2005-2007-2009-2012)

**Scope**

This Recommendation provides guidance on outdoor short-range propagation over the frequency range 300 MHz to 100 GHz. Information is given on path loss models for line-of-sight (LoS) and non-line-of-sight (NLoS) environments, building entry loss, multipath models for both environments of street canyon and over roof-tops, number of signal components, polarization characteristics and fading characteristics.

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 should 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, delay spread and angular 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 very high-rise	<ul style="list-style-type: none"> <li>– Busiest urban deep canyon, characterized by streets lined with high-density buildings with several tens of floors which results in an urban deep canyon</li> <li>– High dense buildings and skyscrapers interleave with each other which yields to the rich scattering propagation paths in NLoS</li> <li>– Rows of tall buildings provide the possibility of very long path delays</li> <li>– Heavy traffic vehicles and high flowrate visitors in the area act as reflectors adding Doppler shift to the reflected waves</li> <li>– Trees beside the streets provide dynamic shadowing</li> </ul>
Urban high-rise	<ul style="list-style-type: none"> <li>– Urban canyon, characterized by streets lined with tall buildings of several floors each</li> <li>– Building height makes significant contributions from propagation over roof-tops unlikely</li> <li>– Rows of tall buildings provide the possibility of long path delays</li> <li>– Large numbers of moving vehicles in the area act as reflectors adding Doppler shift to the reflected waves</li> </ul>
Urban/suburban low-rise	<ul style="list-style-type: none"> <li>– Typified by wide streets</li> <li>– Building heights are generally less than three stories making diffraction over roof-top likely</li> <li>– Reflections and shadowing from moving vehicles can sometimes occur</li> <li>– Primary effects are long delays and small Doppler shifts</li> </ul>

TABLE 1 (*end*)

<b>Environment</b>	<b>Description and propagation impairments of concern</b>
Residential	<ul style="list-style-type: none"> <li>– Single and double storey dwellings</li> <li>– Roads are generally two lanes wide with cars parked along sides</li> <li>– Heavy to light foliage possible</li> <li>– Motor traffic usually light</li> </ul>
Rural	<ul style="list-style-type: none"> <li>– Small houses surrounded by large gardens</li> <li>– Influence of terrain height (topography)</li> <li>– Heavy to light foliage possible</li> <li>– Motor traffic sometimes high</li> </ul>

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**

<b>Environment</b>	<b>Velocity for pedestrian users (m/s)</b>	<b>Velocity for vehicular users</b>
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**

<b>Cell type</b>	<b>Cell radius</b>	<b>Typical position of base station antenna</b>
Micro-cell	0.05 to 1 km	Outdoor; mounted above average roof-top level, heights of some surrounding buildings may be above base station antenna height
Dense urban micro-cell	0.05 to 0.5 km	Outdoor; mounted below average roof-top level
Pico-cell	Up to 50 m	Indoor or outdoor (mounted below roof-top level)

(Note that “dense urban micro-cell” is not explicitly defined in Radiocommunication Study Group 5 Recommendation.)



### 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<sub>1</sub> is mounted above roof-top level. The corresponding cell is a micro-cell. Propagation from this BS is mainly over the roof-tops. Base station BS<sub>2</sub> is mounted below roof-top level and defines a dense urban 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<sub>2</sub> may be used.

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

The typical NLoS case (link BS<sub>1</sub>-MS<sub>1</sub> in Fig. 1) is described by Fig. 2. In the following, this case is called NLoS1.

FIGURE 1  
Typical propagation situation in urban areas

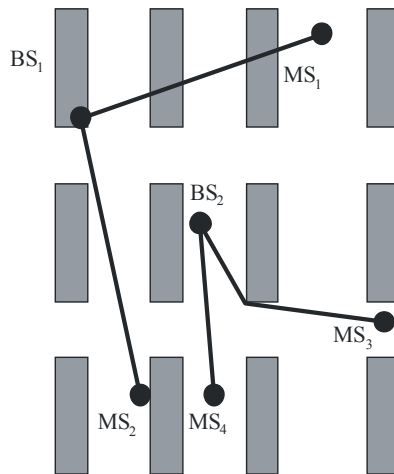
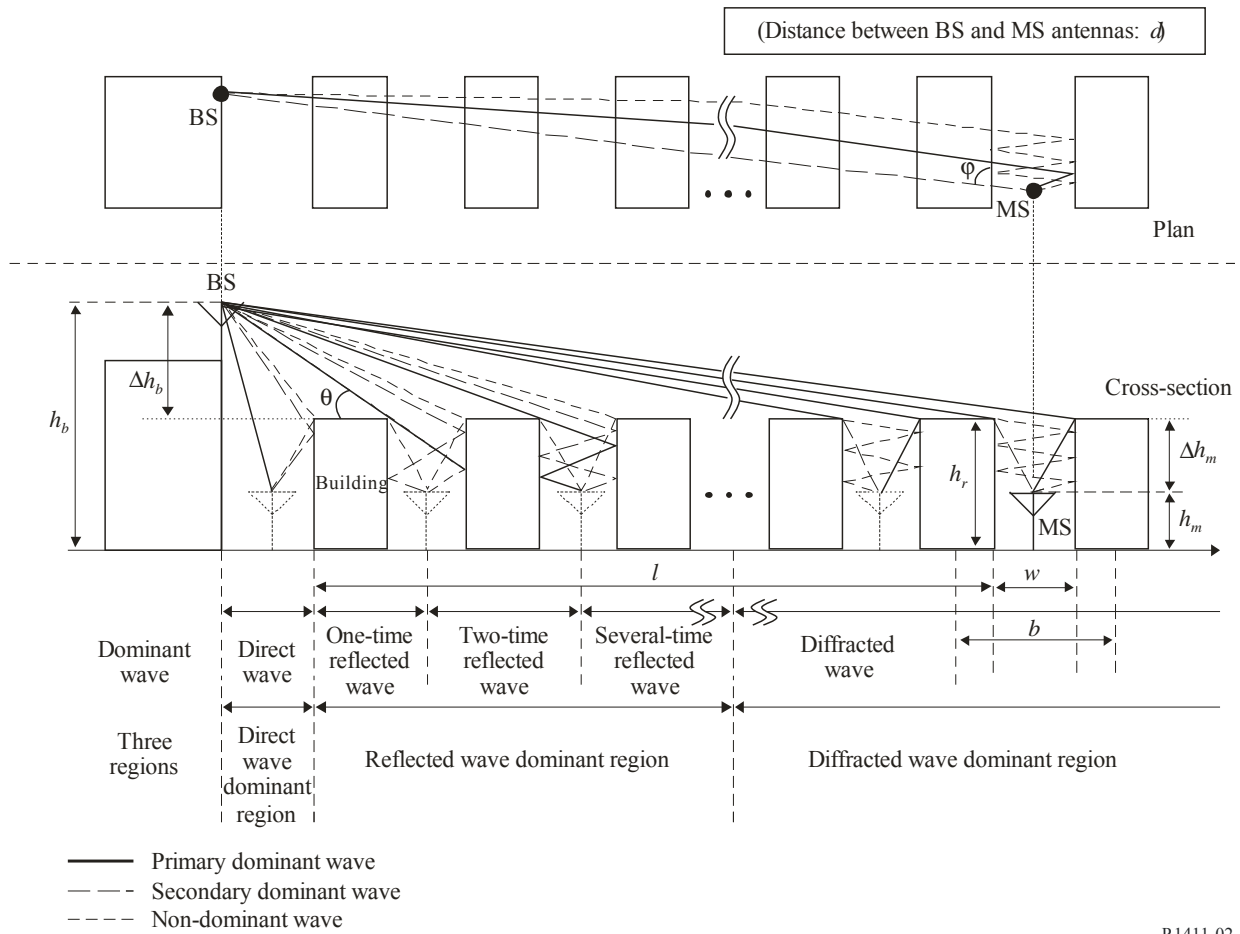


FIGURE 2  
Definition of parameters for the NLoS1 case



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The relevant parameters for this situation are:

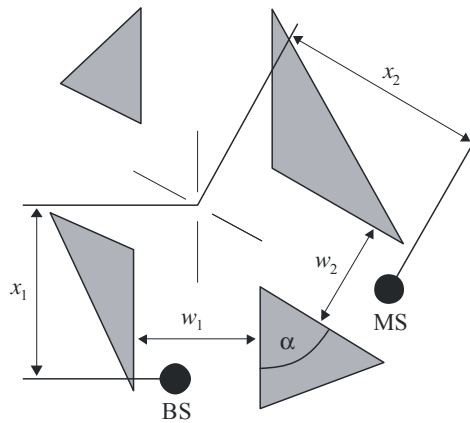
- $h_r$ : average height of buildings (m)
- $w$ : street width (m)
- $b$ : average building separation (m)
- $\phi$ : street orientation with respect to the direct path (degrees)
- $h_b$ : BS antenna height (m)
- $h_m$ : MS antenna height (m)
- $l$ : length of the path covered by buildings (m)
- $d$ : distance from BS to MS.

The NLoS1 case frequently occurs in residential/rural environments for all cell-types and is predominant for micro-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  $\phi$  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 dense urban micro-cellular NLoS-case (link BS<sub>2</sub>-MS<sub>3</sub> in Fig. 1). In the following, this case is called NLoS2.

FIGURE 3  
Definition of parameters for the NLoS2 case



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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)
- $\alpha$ : is the corner angle (rad).

NLoS2 is the predominant path type in urban high-rise environments for all cell-types and occurs frequently in dense urban 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:

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

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

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

where  $\lambda$  is the wavelength (m). The lower bound is based on two-ray ground reflective model.

An approximate upper bound is given by:

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

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

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

The upper bound has the fading margin of 20 dB. In equation (3), the attenuation coefficient before breakpoint is set to 2.5 because a short distance leads to weak shadowing effect.

According to the free-space loss curve, a median value is given by:

$$L_{LoS,m} = L_{bp} + 6 + \begin{cases} 20 \log_{10} \left( \frac{d}{R_{bp}} \right) & \text{for } d \leq R_{bp} \\ 40 \log_{10} \left( \frac{d}{R_{bp}} \right) & \text{for } d > R_{bp} \end{cases} \quad (5)$$

#### 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:

$$R_{bp} = 4 \frac{(h_b - h_s)(h_m - h_s)}{\lambda} \quad (6)$$

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:

$$L_{bp} = \left| 20 \log_{10} \left\{ \frac{\lambda^2}{8\pi(h_b - h_s)(h_m - h_s)} \right\} \right| \quad (7)$$

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:

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

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

$$L_{LoS,u} = L_s + 20 + 30 \log_{10} \left( \frac{d}{R_s} \right) \quad (9)$$

The basic propagation loss  $L_s$  is defined as:

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

$R_s$  in equations (8) to (10) has been experimentally determined to be 20 m.

Based on measurements, a median value is given by:

$$L_{LoS,m} = L_s + 6 + 30 \log_{10} \left( \frac{d}{R_s} \right) \quad (11)$$

*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.

*Propagation for urban area*

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 5 000 MHz  
2 to 16 GHz for  $h_b < h_r$  and  $w_2 < 10$  m (or sidewalk)
- $d$ : 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.)

*Propagation for suburban area*

Model is defined for the situation of  $h_b > h_r$  described in § 3.1. The model is valid for:

- $h_r$ : any height m
- $\Delta h_b$ : 1 to 100 m
- $\Delta h_m$ : 4 to 10 (less than  $h_r$ ) m
- $h_b$ :  $h_r + \Delta h_b$  m
- $h_m$ :  $h_r - \Delta h_m$  m
- $f$ : 0.8 to 20 GHz
- $w$ : 10 to 25 m
- $d$ : 10 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 for urban area

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  $l$  (see 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.

$$L_{NLoS1} = \begin{cases} L_{bf} + L_{rts} + L_{msd} & \text{for } L_{rts} + L_{msd} > 0 \\ L_{bf} & \text{for } L_{rts} + L_{msd} \leq 0 \end{cases} \quad (12)$$

The free-space loss is given by:

$$L_{bf} = 32.4 + 20 \log_{10} (d / 1\,000) + 20 \log_{10} (f) \quad (13)$$

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.

$$L_{rts} = -8.2 - 10 \log_{10} (w) + 10 \log_{10} (f) + 20 \log_{10} (\Delta h_m) + L_{ori} \quad (14)$$

$$L_{ori} = \begin{cases} -10 + 0.354\varphi & \text{for } 0^\circ \leq \varphi < 35^\circ \\ 2.5 + 0.075(\varphi - 35) & \text{for } 35^\circ \leq \varphi < 55^\circ \\ 4.0 - 0.114(\varphi - 55) & \text{for } 55^\circ \leq \varphi \leq 90^\circ \end{cases} \quad (15)$$

where:

$$\Delta h_m = h_r - h_m \quad (16)$$

$L_{ori}$  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. 2).

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”,  $d_s$ :

$$d_s = \frac{\lambda d^2}{\Delta h_b^2} \quad (17)$$

where (see Fig. 2):

$$\Delta h_b = h_b - h_r \quad (18)$$

For the calculation of  $L_{msd}$ ,  $d_s$  is compared to the distance  $l$  over which the buildings extend. The calculation for  $L_{msd}$  uses the following procedure to remove any discontinuity between the different models used when the length of buildings is greater or less than the “settled field distance”.

The overall multiple screen diffraction model loss is given by:

$$L_{msd} = \begin{cases} -\tanh\left(\frac{\log(d) - \log(d_{bp})}{\chi}\right) \cdot (L1_{msd}(d) - L_{mid}) + L_{mid} & \text{for } l > d_s \text{ and } dh_{bp} > 0 \\ \tanh\left(\frac{\log(d) - \log(d_{bp})}{\chi}\right) \cdot (L2_{msd}(d) - L_{mid}) + L_{mid} & \text{for } l \leq d_s \text{ and } dh_{bp} > 0 \\ L2_{msd}(d) & \text{for } dh_{bp} = 0 \\ L1_{msd}(d) - \tanh\left(\frac{\log(d) - \log(d_{bp})}{\zeta}\right) \cdot (L_{upp} - L_{mid}) - L_{upp} + L_{mid} & \text{for } l > d_s \text{ and } dh_{bp} < 0 \\ L2_{msd}(d) + \tanh\left(\frac{\log(d) - \log(d_{bp})}{\zeta}\right) \cdot (L_{mid} - L_{low}) + L_{mid} - L_{low} & \text{for } l \leq d_s \text{ and } dh_{bp} < 0 \end{cases} \quad (19)$$

where:

$$dh_{bp} = L_{upp} - L_{low} \quad (20)$$

$$\zeta = (L_{upp} - L_{low}) \cdot \nu \quad (21)$$

$$L_{mid} = \frac{(L_{upp} + L_{low})}{2} \quad (22)$$

$$L_{upp} = L1_{msd}(d_{bp}) \quad (23)$$

$$L_{low} = L2_{msd}(d_{bp}) \quad (24)$$

and

$$d_{bp} = |\Delta h_b| \sqrt{\frac{l}{\lambda}} \quad (25)$$

$$\nu = [0.0417]$$

$$\chi = [0.1]$$

where the individual model losses,  $L1_{msd}(d)$  and  $L2_{msd}(d)$ , are defined as follows:



Calculation of  $L1_{msd}$  for  $l > d_s$

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

$$L1_{msd}(d) = L_{bsh} + k_a + k_d \log_{10}(d / 1\ 000) + k_f \log_{10}(f) - 9 \log_{10}(b) \quad (26)$$

where:

$$L_{bsh} = \begin{cases} -18 \log_{10}(1 + \Delta h_b) & \text{for } h_b > h_r \\ 0 & \text{for } h_b \leq h_r \end{cases} \quad (27)$$

is a loss term that depends on the BS height:

$$k_a = \begin{cases} 71.4 & \text{for } h_b > h_r \text{ and } f > 2\ 000 \text{ MHz} \\ 73 - 0.8\Delta h_b & \text{for } h_b \leq h_r, f > 2\ 000 \text{ MHz and } d \geq 500 \text{ m} \\ 73 - 1.6\Delta h_b d / 1\ 000 & \text{for } h_b \leq h_r, f > 2\ 000 \text{ MHz and } d < 500 \text{ m} \\ 54 & \text{for } h_b > h_r \text{ and } f \leq 2\ 000 \text{ MHz} \\ 54 - 0.8\Delta h_b & \text{for } h_b \leq h_r, f \leq 2\ 000 \text{ MHz and } d \geq 500 \text{ m} \\ 54 - 1.6\Delta h_b d / 1\ 000 & \text{for } h_b \leq h_r, f \leq 2\ 000 \text{ MHz and } d < 500 \text{ m} \end{cases} \quad (28)$$

$$k_d = \begin{cases} 18 & \text{for } h_b > h_r \\ 18 - 15 \frac{\Delta h_b}{h_r} & \text{for } h_b \leq h_r \end{cases} \quad (29)$$

$$k_f = \begin{cases} -8 & \text{for } f > 2\ 000 \text{ MHz} \\ -4 + 0.7(f / 925 - 1) & \text{for medium sized city and suburban} \\ & \text{centres with medium tree density and } f \leq 2\ 000 \text{ MHz} \\ -4 + 1.5(f / 925 - 1) & \text{for metropolitan centres and } f \leq 2\ 000 \text{ MHz} \end{cases} \quad (30)$$

Calculation of  $L2_{msd}$  for  $l < d_s$

In this case a further distinction has to be made according to the relative heights of the BS and the roof-tops:

$$L2_{msd}(d) = -10 \log_{10}(Q_M^2) \quad (31)$$

where:

$$Q_M = \begin{cases} 2.35 \left( \frac{\Delta h_b}{d} \sqrt{\frac{b}{\lambda}} \right)^{0.9} & \text{for } h_b > h_r + \delta h_u \\ \frac{b}{d} & \text{for } h_b \leq h_r + \delta h_u \text{ and } h_b \geq h_r + \delta h_l \\ \frac{b}{2\pi d} \sqrt{\frac{\lambda}{\rho}} \left( \frac{1}{\theta} - \frac{1}{2\pi + \theta} \right) & \text{for } h_b < h_r + \delta h_l \end{cases} \quad (32)$$

and

$$\theta = \arctan\left(\frac{\Delta h_b}{b}\right) \quad (33)$$

$$\rho = \sqrt{\Delta h_b^2 + b^2} \quad (34)$$

and

$$\delta h_u = 10^{-\log_{10}\left(\sqrt{\frac{b}{\lambda}}\right) - \frac{\log_{10}(d)}{9} + \frac{10}{9}\log_{10}\left(\frac{b}{2.35}\right)} \quad (35)$$

$$\delta h_l = \frac{0.00023b^2 - 0.1827b - 9.4978}{(\log_{10}(f))^{2.938}} + 0.000781b + 0.06923 \quad (36)$$

#### 4.2.2 Propagation over roof-tops for suburban area

A propagation model for the NLoS1-Case based on geometrical optics (GO) is shown in Fig. 2. This figure indicates that the composition of the arriving waves at the MS changes according to the BS-MS distance. A direct wave can arrive at the MS only when the BS-MS distance is very short. The several-time (one-, two-, or three-time) reflected waves, which have a relatively strong level, can arrive at the MS when the BS-MS separation is relatively short. When the BS-MS separation is long, the several-time reflected waves cannot arrive and only many-time reflected waves, which have weak level beside that of diffracted waves from building roofs, arrive at the MS. Based on these propagation mechanisms, the loss due to the distance between isotropic antennas can be divided into three regions in terms of the dominant arrival waves at the MS. These are the direct wave, reflected wave, and diffracted wave dominant regions. The loss in each region is expressed as follows based on GO.

$$L_{NLoS1} = \begin{cases} 20 \cdot \log_{10}\left(\frac{4\pi d}{\lambda}\right) & \text{for } d < d_0 \quad (\text{Direct wave dominant region}) \\ L_{0n} & \text{for } d_0 \leq d < d_{RD} \quad (\text{Reflected wave dominant region}) \\ 32.1 \cdot \log_{10}\left(\frac{d}{d_{RD}}\right) + L_{d_{RD}} & \text{for } d \geq d_{RD} \quad (\text{Diffracted wave dominant region}) \end{cases} \quad (37)$$

where:

$$L_{0n} = \begin{cases} L_{d_k} + \frac{L_{d_{k+1}} - L_{d_k}}{d_{k+1} - d_k} \cdot (d - d_k) & \text{when } d_k \leq d < d_{k+1} < d_{RD} \\ & (k = 0, 1, 2, \dots) \\ L_{d_k} + \frac{L_{d_{RD}} - L_{d_k}}{d_{RD} - d_k} \cdot (d - d_k) & \text{when } d_k \leq d < d_{RD} < d_{k+1} \end{cases} \quad (38)$$

$$d_k = \frac{1}{\sin \varphi} \cdot \sqrt{B_k^2 + (h_b - h_m)^2} \quad (39)$$

$$L_{d_k} = 20 \cdot \log_{10} \left\{ \frac{4\pi d_{kp}}{0.4^k \cdot \lambda} \right\} \quad (40)$$

$$d_{RD}(f) = 0.625 \cdot (d_3 - d_1) \cdot \log_{10}(f) + 0.44 \cdot d_1 + 0.5 \cdot d_2 + 0.06 \cdot d_3 \quad (41)$$

(0.8 GHz  $\leq$   $f$   $\leq$  20 GHz)

$$L_{d_{RD}} = L_{d_k} + \frac{L_{d_{k+1}} - L_{d_k}}{d_{k+1} - d_k} \cdot (d_{RD} - d_k) \quad (d_k \leq d_{RD} \leq d_{k+1}) \quad (42)$$

$$d_{kp} = \frac{1}{\sin \varphi_k} \cdot \sqrt{A_k^2 + (h_b - h_m)^2} \quad (43)$$

$$A_k = \frac{w \cdot (h_b - h_m) \cdot (2k + 1)}{2 \cdot (h_r - h_m)} \quad (44)$$

$$B_k = \frac{w \cdot (h_b - h_m) \cdot (2k + 1)}{2 \cdot (h_r - h_m)} - k \cdot w \quad (45)$$

$$\varphi_k = \tan^{-1} \left( \frac{B_k}{A_k} \cdot \tan \varphi \right) \quad (46)$$

### 4.2.3 Propagation within street canyons for frequency range from 800 to 2000 MHz

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).

$$L_{NLoS2} = -10 \log_{10} \left( 10^{-L_r/10} + 10^{-L_d/10} \right) \quad \text{dB} \quad (47)$$

where:

$L_r$ : reflection path loss defined by:

$$L_r = 20 \log_{10} (x_1 + x_2) + x_1 x_2 \frac{f(\alpha)}{w_1 w_2} + 20 \log_{10} \left( \frac{4\pi}{\lambda} \right) \quad \text{dB} \quad (48)$$

where:

$$f(\alpha) = \frac{3.86}{\alpha^{3.5}} \quad \text{dB} \quad (49)$$

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

$L_d$ : diffraction path loss defined by:

$$L_d = 10 \log_{10} [x_1 x_2 (x_1 + x_2)] + 2D_a - 0.1 \left( 90 - \alpha \frac{180}{\pi} \right) + 20 \log_{10} \left( \frac{4\pi}{\lambda} \right) \quad \text{dB} \quad (50)$$

$$D_a = \left( \frac{40}{2\pi} \right) \left[ \arctan\left(\frac{x_2}{w_2}\right) + \arctan\left(\frac{x_1}{w_1}\right) - \frac{\pi}{2} \right] \quad \text{dB} \quad (51)$$

#### 4.2.4 Propagation within street canyons for frequency range from 2 to 16 GHz

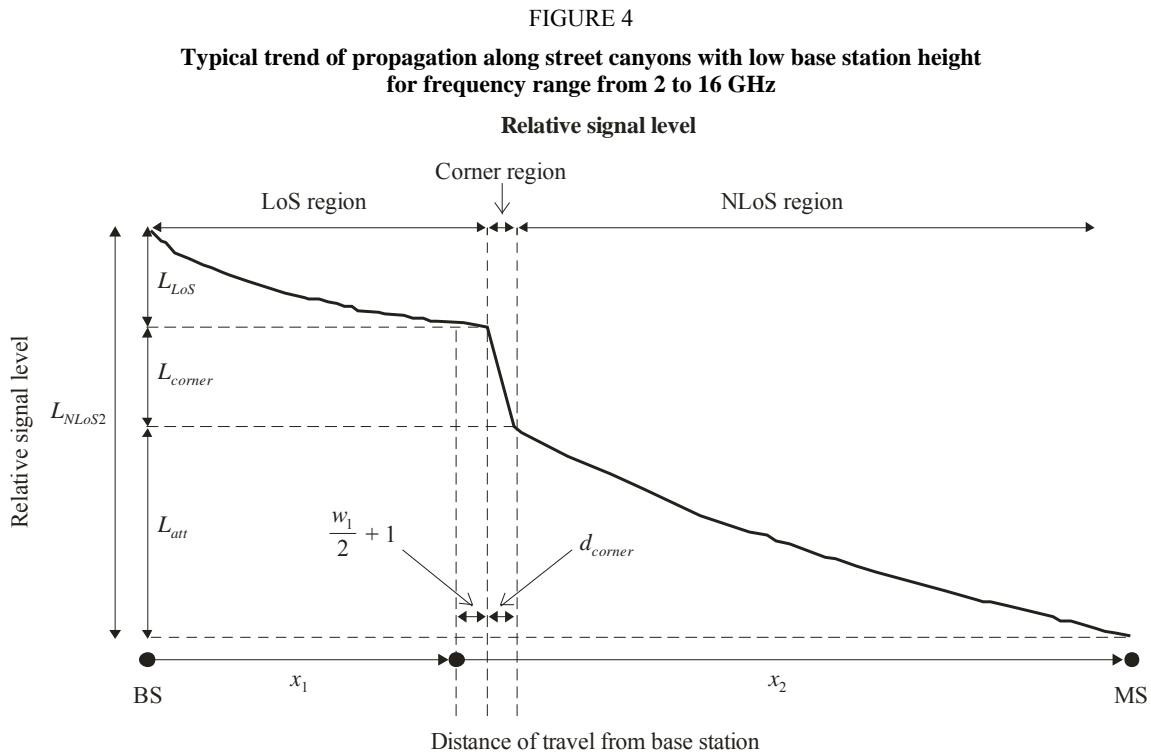
The propagation model for the NLoS2 situations as described in § 3.1.2 with the corner angle  $\alpha = \pi/2$  rad is derived based on measurements at a frequency range from 2 to 16 GHz, where  $h_b < h_r$  and  $w_2$  is up to 10 m (or sidewalk). The path loss characteristics can be divided into two parts: the corner loss region and the NLoS region. The corner loss region extends for  $d_{corner}$  from the point which is 1 m down the edge of the LoS street into the NLoS street. The corner loss ( $L_{corner}$ ) is expressed as the additional attenuation over the distance  $d_{corner}$ . The NLoS region lies beyond the corner loss region, where a coefficient parameter ( $\beta$ ) applies. This is illustrated by the typical curve shown in Fig. 4. Using  $x_1$ ,  $x_2$ , and  $w_1$ , as shown in Fig. 3, the overall path loss ( $L_{NLoS2}$ ) beyond the corner region ( $x_2 > w_1/2 + 1$ ) is found using:

$$L_{NLoS2} = L_{LoS} + L_c + L_{att} \quad (52)$$

$$L_c = \begin{cases} \frac{L_{corner}}{\log_{10}(1+d_{corner})} \log_{10}(x_2 - w_1/2) & w_1/2 + 1 < x_2 \leq w_1/2 + 1 + d_{corner} \\ L_{corner} & x_2 > w_1/2 + 1 + d_{corner} \end{cases} \quad (53)$$

$$L_{att} = \begin{cases} 10\beta \log_{10}\left(\frac{x_1 + x_2}{x_1 + w_1/2 + d_{corner}}\right) & x_2 > w_1/2 + 1 + d_{corner} \\ 0 & x_2 > w_1/2 + 1 + d_{corner} \end{cases} \quad (54)$$

where  $L_{LoS}$  is the path loss in the LoS street for  $x_1 (> 20 \text{ m})$ , as calculated in § 4.1. In equation (53),  $L_{corner}$  is given as 20 dB in an urban environment and 30 dB in a residential environment. And  $d_{corner}$  is 30 m in both environments. In equation (54),  $\beta$  is given by 6 in both environments.



In a residential environment, the path loss does not increase monotonically with distance, and thus the coefficient parameter may be lower than the value in an urban environment, owing to the presence of alleys and gaps between the houses.

With a high base station antenna in the small macro-cell, the effects of diffraction over roof-tops are more significant. Consequently, the propagation characteristics do not depend on the corner loss.

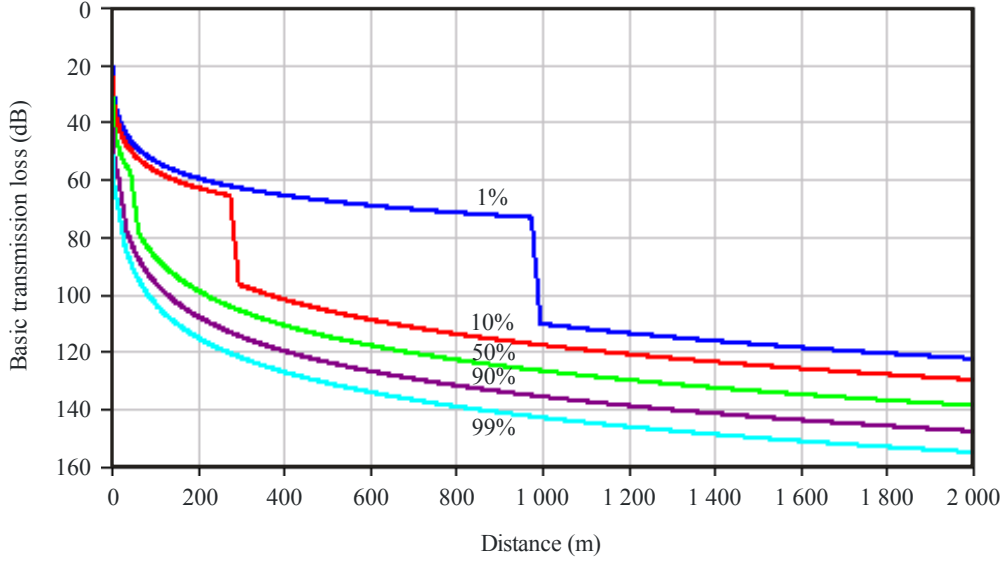
### 4.3 Propagation between terminals located below roof-top height at UHF

The model described below is intended for calculating the basic transmission loss between two terminals of low height in urban environments. It includes both LoS and NLoS regions, and models the rapid decrease in signal level noted at the corner between the LoS and NLoS regions. The model includes the statistics of location variability in the LoS and NLoS regions, and provides a statistical model for the corner distance between the LoS and NLoS regions. Figure 5 illustrates the LoS, NLoS and corner regions, and the statistical variability predicted by the model.

This model is recommended for propagation between low-height terminals where both terminal antenna heights are near street level well below roof-top height, but are otherwise unspecified. It is reciprocal with respect to transmitter and receiver and is valid for frequencies in the range 300-3 000 MHz. The model is based on measurements made in the UHF band with antenna heights between 1.9 and 3.0 m above ground, and transmitter-receiver distances up to 3 000 m.

FIGURE 5

Curves of basic transmission loss not exceeded for 1, 10, 50, 90 and 99% of locations  
(frequency = 400 MHz, suburban)



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The parameters required are the frequency  $f$  (MHz) and the distance between the terminals  $d$  (m).

*Step 1:* Calculate the median value of the line-of-sight loss:

$$L_{LoS}^{median}(d) = 32.45 + 20 \log_{10} f + 20 \log_{10}(d/1000) \quad (55)$$

*Step 2:* For the required location percentage,  $p$  (%), calculate the LoS location correction:

$$\Delta L_{LoS}(p) = 1.5624\sigma \left( \sqrt{-2 \ln(1-p/100)} - 1.1774 \right) \quad \text{with } \sigma = 7 \text{ dB} \quad (56)$$

Alternatively, values of the LoS correction for  $p = 1, 10, 50, 90$  and  $99\%$  are given in Table 6.

*Step 3:* Add the LoS location correction to the median value of LoS loss:

$$L_{LoS}(d, p) = L_{LoS}^{median}(d) + \Delta L_{LoS}(p) \quad (57)$$

*Step 4:* Calculate the median value of the NLoS loss:

$$L_{NLoS}^{median}(d) = 9.5 + 45 \log_{10} f + 40 \log_{10}(d/1000) + L_{urban} \quad (58)$$

$L_{urban}$  depends on the urban category and is 0 dB for suburban, 6.8 dB for urban and 2.3 dB for dense urban/high-rise.

*Step 5:* For the required location percentage,  $p$  (%), add the NLoS location correction:

$$\Delta L_{NLoS}(p) = \sigma N^{-1}(p/100) \quad \text{with } \sigma = 7 \text{ dB} \quad (59)$$

$N^{-1}(\cdot)$  is the inverse normal cumulative distribution function. An approximation to this function, good for  $p$  between 1 and 99% is given by the location variability function  $Q_i(x)$



of Recommendation ITU-R P.1546. Alternatively, values of the NLoS location correction for  $p = 1, 10, 50, 90$  and  $99\%$  are given in Table 6.

TABLE 6

**Table of LoS and NLoS location variability corrections**

$p$ (%)	$\Delta L_{LoS}$ (dB)	$\Delta L_{NLoS}$ (dB)	$d_{LoS}$ (m)
1	-11.3	-16.3	976
10	-7.9	-9.0	276
50	0.0	0.0	44
90	10.6	9.0	16
99	20.3	16.3	10

*Step 6:* Add the NLoS location correction to the median value of NLoS loss:

$$L_{NLoS}(d, p) = L_{NLoS}^{median}(d) + \Delta L_{NLoS}(p) \quad (60)$$

*Step 7:* For the required location percentage,  $p$  (%), calculate the distance  $d_{LoS}$  for which the LoS fraction  $F_{LoS}$  equals  $p$ :

$$\begin{aligned} d_{LoS}(p) &= 212[\log_{10}(p/100)]^2 - 64 \log_{10}(p/100) && \text{if } p < 45 \\ d_{LoS}(p) &= 79.2 - 70(p/100) && \text{otherwise} \end{aligned} \quad (61)$$

Values of  $d_{LoS}$  for  $p = 1, 10, 50, 90$  and  $99\%$  are given in Table 6. This model has not been tested for  $p < 0.1\%$ . The statistics were obtained from two cities in the United Kingdom and may be different in other countries. Alternatively, if the corner distance is known in a particular case, set  $d_{LoS}(p)$  to this distance.

*Step 8:* The path loss at the distance  $d$  is then given as:

- If  $d < d_{LoS}$ , then  $L(d, p) = L_{LoS}(d, p)$
- If  $d > d_{LoS} + w$ , then  $L(d, p) = L_{NLoS}(d, p)$
- Otherwise linearly interpolate between the values  $L_{LoS}(d_{LoS}, p)$  and  $L_{NLoS}(d_{LoS} + w, p)$ :

$$\begin{aligned} L_{LoS} &= L_{LoS}(d_{LoS}, p) \\ L_{NLoS} &= L_{NLoS}(d_{LoS} + w, p) \\ L(d, p) &= L_{LoS} + (L_{NLoS} - L_{LoS})(d - d_{LoS})/w \end{aligned}$$

The width  $w$  is introduced to provide a transition region between the LoS and NLoS regions. This transition region is seen in the data and typically has a width of  $w = 20$  m.

#### 4.4 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:

$$h_r = 3 \times (\text{number of floors}) + \text{roof-height (m)}$$

$$\begin{aligned}\text{roof-height} &= 3 \text{ m for pitched roofs} \\ &= 0 \text{ m for flat roofs} \\ w &= b/2 \\ b &= 20 \text{ to } 50 \text{ m} \\ \varphi &= 90^\circ.\end{aligned}$$

#### 4.5 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 7 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 7

**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 8 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 8

**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

#### 6.1.1 Omnidirectional antenna case

Characteristics of multipath delay spread for the LoS omnidirectional antenna case in an urban high-rise environment for dense urban 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:

$$a_s = C_a d^{\gamma_a} \quad \text{ns} \quad (62)$$

and the standard deviation given by:

$$\sigma_s = C_\sigma d^{\gamma_\sigma} \quad \text{ns} \quad (63)$$

where  $C_a$ ,  $\gamma_a$ ,  $C_\sigma$  and  $\gamma_\sigma$  depend on the antenna height and propagation environment. Table 9 lists some typical values of the coefficients for distances of 50-400 m based on measurements made in urban and residential areas.

TABLE 9

**Typical coefficients for the distance characteristics of r.m.s. delay spread  
for omnidirectional antenna case**

Measurement conditions				$a_s$		$\sigma_s$	
Area	$f$ (GHz)	$h_b$ (m)	$h_m$ (m)	$C_a$	$\gamma_a$	$C_\sigma$	$\gamma_\sigma$
Urban <sup>(1)</sup>	0.781	5	5	1 254.3	0.06	102.2	0.04
Urban <sup>(2)</sup>	2.5	6.0	3.0	55	0.27	12	0.32
	3.35-15.75	4.0	2.7	23	0.26	5.5	0.35
			1.6	10	0.51	6.1	0.39
	3.35-8.45	0.5					
Residential <sup>(2)</sup>	3.35	4.0	2.7	2.1	0.53	0.54	0.77
	3.35-15.75		1.6	5.9	0.32	2.0	0.48

(1) Threshold value of 20 dB is used for r.m.s. delay spread calculation.

(2) Threshold value of 30 dB is used for r.m.s. delay spread calculation.

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

$$P(t) = P_0 + 50(e^{-t/\tau} - 1) \quad \text{dB} \quad (64)$$

where:

$P_0$ : peak power (dB)

$\tau$ : decay factor

and  $t$  is in ns.

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

$$\tau = 4 S + 266 \quad \text{ns} \quad (65)$$

A linear relationship between  $\tau$  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.)

### 6.1.2 Directional antenna case

In fixed wireless access systems and communications between the access points of wireless mesh network systems, directional antennas are employed as transmitter and receiver antennas. A typical effect of the use of directional antennas is given hereafter. Arriving delayed waves are suppressed by the antenna pattern using directional antennas as the transmitter and receiver antennas. Therefore, the delay spread becomes small. In addition, the received power increases with the antenna gain, when directional antennas are employed as the transmitter and receiver antennas. Based on these facts, the directional antenna is used in wireless systems. Therefore, it is important to understand the effect of antenna directivity in multipath models.

Characteristics of the multipath delay spread for the LoS directional antenna case in an urban high-rise environment for dense urban micro-cells and pico-cells (as defined in Table 3) were developed based on measured data in the 5.2 GHz band at distances from 10 to 500 m. The antennas were configured such that the direction of the maximum antenna gain of one antenna faced that of the other. Table 10 lists equation for deriving coefficients relative to the antenna half power beamwidth for formula (58) for distances of 10-500 m based on measurements in an urban area. These equations are only depending on the antenna half power beamwidth and effective to any width of the road.

TABLE 10

**Typical coefficients for the distance characteristics of r.m.s. delay spread  
for directional antenna case**

Measurement conditions				$a_s$	
Area	$f$ (GHz)	$h_b$ (m)	$h_m$ (m)	$C_a$	$\gamma_a$
Urban	5.2	3.5	3.5	$9.3 + 1.5\log(\theta)$	$3.3 \times 10^{-2} + 4.6\theta \times 10^{-2}$

NOTE 1 – Threshold value of 20 dB is used for r.m.s. delay spread calculation.

Here,  $\theta$  represents antenna half-power beamwidth at both transmitting and receiving antenna and the unit is radian. Note that  $\theta$  should be set to  $2\pi$  when omnidirectional antenna is applied to both transmitting and receiving antenna.

## 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 micro-cells (as defined in Table 3) have been developed based on measured data at 1 920-1 980 MHz, 2 110-2 170 MHz, and 3 650-3 750 MHz using omnidirectional antennas. The median r.m.s. delay spread  $S$  in this environment is given by:

$$S_u = \exp(A \cdot L + B) \quad \text{ns} \quad (66)$$

where both A and B are coefficients of r.m.s. delay spread and  $L$  is path loss (dB). Table 11 lists the typical values of the coefficients for distances of 100 m – 1 km based on measurements made in urban areas.

TABLE 11

**Typical coefficients for r.m.s. delay spread**

Measurement conditions			Coefficients of r.m.s. delay spread	
Area	Frequency (GHz)	Range (m)	A	B
Urban	3 650-3 750 MHz	100-1 000	0.031	2.091
	1 920-1 980 MHz, 2 110-2 170 MHz	100-1 000	0.038	2.3

The distributions of the multipath delay characteristics for the 3.7 GHz band in an urban environment with each BS antenna height of 40 m and 60 m, and MS antenna height of 2 m were derived from measurements. The distributions of the multipath delay characteristics for the 3.7 GHz and 5.2 GHz band in a suburban environment with a BS antenna height of 20 m, and MS antenna height of 2.0 m and 2.8 m were derived from measurements. Table 12 lists the measured r.m.s. delay spread for the 3.7 GHz and 5.2 GHz band for cases where the cumulative probability is 50% and 95%.

TABLE 12  
Typical r.m.s. delay spread values\*

Measurement conditions						r.m.s. delay spread (ns)	
Area	Scenario	Frequency (GHz)	Antenna height		Range (m)	50%	95%
			$h_{BS}$ (m)	$h_r$ (m)			
Urban very high-rise	LoS	2.5	100	2	100-1 000	208	461
	NLoS					407	513
Urban		3.7	60	2	100-1 000	232	408
			40	2	100-1 000	121	357
Suburban		3.7	20	2	100-1 000	125	542
		5.2	20	2.8	100-1 000	189	577

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

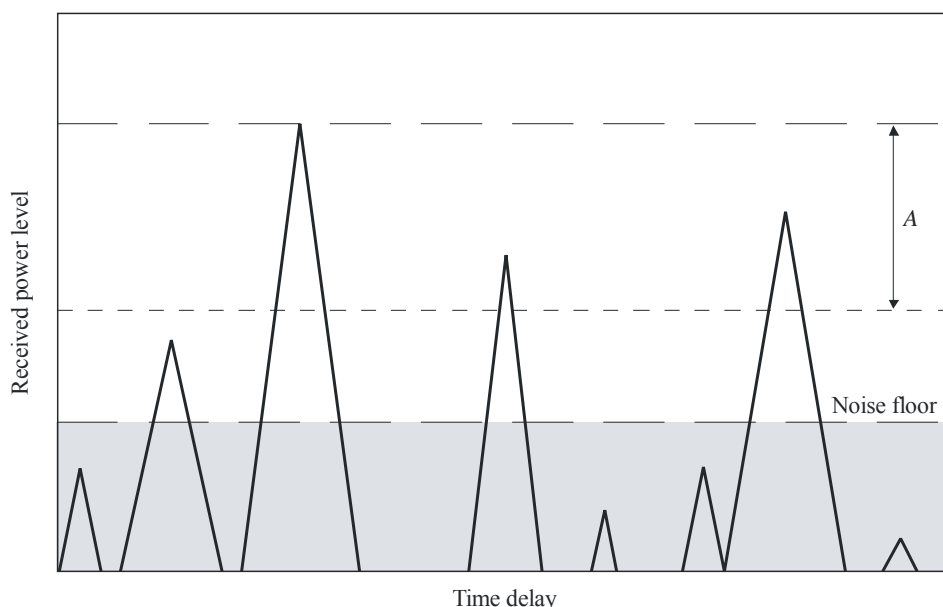
## 7 Number of signal components

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. 6.



FIGURE 6

Definition for the determination of the number of peaks



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Table 13 shows the results for the number of signal components from measurements in different scenarios for different antenna heights, environments and for different frequencies.

TABLE 13

Maximum number of signal components

Type of environment	Time delay resolution	Frequency (GHz)	Antenna height (m)		Range (m)	Maximum number of components					
			$h_b$	$h_m$		3 dB		5 dB		10 dB	
						80%	95%	80%	95%	80%	95%
Urban	200 ns	1.9-2.1	46	1.7	100-1 600	1	2	1	2	2	4
Suburban	175 ns	2.5	12	1	200-1 500	1	2	1	2	2	4
Urban	20 ns	3.35	4	1.6	0-200	2	3	2	4	5	6
					0-1 000	2	3	2	4	5	9
			55	2.7	150-590	2	2	2	3	3	13
Residential	20 ns	3.35	4	2.7	0-480	2	2	2	2	2	3
Suburban	175 ns	3.5	12	1	200-1 500	1	2	1	2	1	5
Suburban	50 ns	3.67	40	2.7	0-5 000	1	2	1	3	3	5
Suburban	100 ns	5.8	12	1	200-1 500	1	2	3	5	4	5
Urban	20 ns	8.45	4	1.6	0-200	1	3	2	3	4	6
					0-1 000	1	2	2	4	4	8
			55	2.7	150-590	2	2	2	3	3	12
Urban	20 ns	15.75	4	1.6	0-200	1	3	2	3	4	5
					0-1 000	2	3	2	4	6	10

For the measurements described in § 6.2, the differential time delay window for the strongest 4 components with respect to the first arriving component and their relative amplitude is given in Table 15.

## **8 Polarization characteristics**

Cross-polarization discrimination (XPD), as defined in Recommendation ITU-R P.310, differs between LoS and NLoS areas in an SHF dense urban 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.

TABLE 14

Type of environment	BS antenna	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%
Urban	Low	3.35	4	1.6	0-200	2	3	2	4	5	6
					0-1 000	2	3	2	4	5	9
Urban	Low	8.45	4	1.6	0-200	1	3	2	3	4	6
					0-1 000	1	2	2	4	4	8
Urban	Low	15.75	4	1.6	0-200	1	3	2	3	4	5
					0-1 000	2	3	2	4	6	10
Urban	High	3.35	55	2.7	150-590	2	2	2	3	3	13
					150-590	2	2	2	3	3	12
Residential	Low	3.35	4	2.7	0-480	2	2	2	2	2	3
Suburban	High	3.67	40	2.7	0-5 000	1	2	1	3	3	5

TABLE 15

**Differential time delay window for the strongest 4 components with respect to the first arriving component and their relative amplitude**

Type of environment	Time delay resolution	Frequency (GHz)	Antenna height (m)		Range (m)	Excess time delay ( $\mu$ s)							
			$h_b$	$h_m$		1st		2nd		3rd		4th	
						80%	95%	80%	95%	80%	95%	80%	95%
Urban	200 ns	1.9-2.1	46	1.7	100-1 600	0.5	1.43	1.1	1.98	1.74	2.93	2.35	3.26
Relative power with respect to strongest component (dB)						0	0	-7.3	-9	-8.5	-9.6	-9.1	-9.8

## 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 dense urban micro-cell 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  $4^\circ$ .

Also measurement performed at the dense urban micro-cell environment in urban area. Angular spread coefficients are introduced based on measurements in urban areas for distances of 10~1 000 m, under the LoS cases at a frequency of 0.781 GHz. Four elements omnidirectional linear array with Bartlett beam-forming method is used for deriving the angular profile.

The coefficients for r.m.s. angular spread were obtained as shown in Table 16.

TABLE 16

**Typical coefficients for the distance characteristics of angular spread**

Measurement conditions				Mean (degree)	s.t.d (degree)	Remark
Area	$f$ (GHz)	$h_b$ (m)	$h_m$ (m)			
Urban	0.781	5	1.5	28.15	13.98	LoS
Urban	8.45	2.7	4.4	30	11	LoS
Urban	8.45	2.7	4.4	41	18	NLoS

## 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  $\Delta L_{max}$  m as shown in Fig. 7.  $\Delta L_{max}$  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. 8. 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 7

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

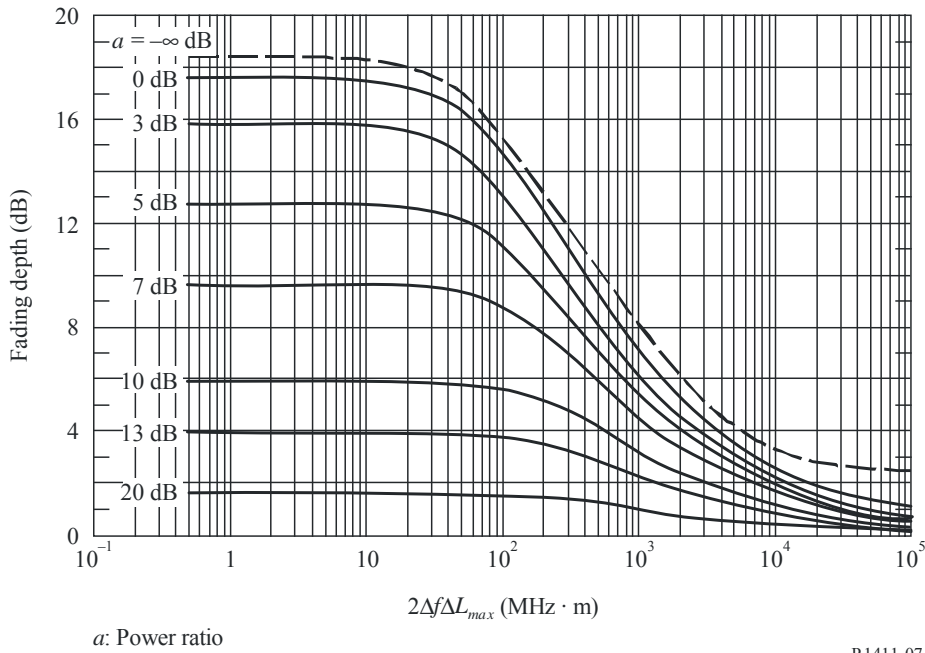
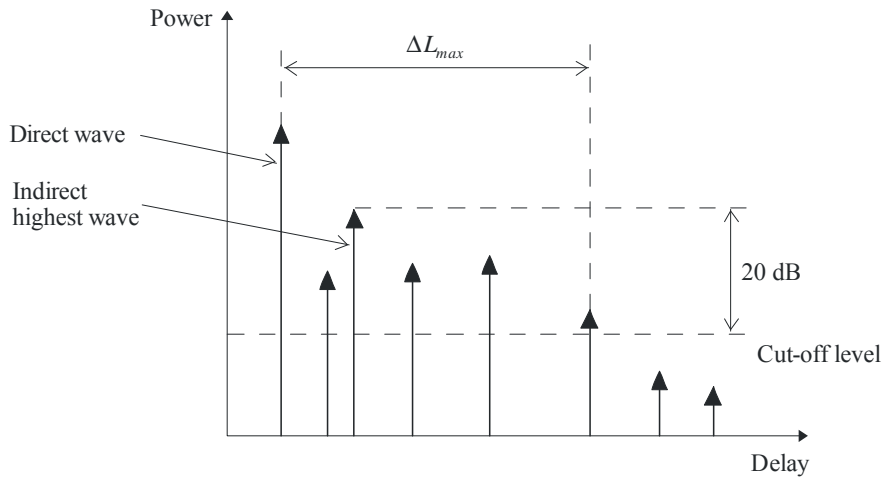


FIGURE 8

Model for calculating  $\Delta L_{max}$



P.1411-08

## 11 Propagation data and prediction methods for the path morphology approach

### 11.1 Classification of path morphology

In the populating area except rural area, the path morphology for wireless channels can be classified into 9 categories as shown in Table 17. The classification is fully based on real wave-propagation environment, by analysing building height and density distribution for various representative locations using GIS (Geographic Information System) database.

TABLE 17

**Classification of path morphologies for the MIMO channel**

Path morphology		density
High rise (above 25 m)	High density (HRHD)	above 35%
	Middle density (HRMD)	20 ~ 35%
	Low density (HRLD)	below 20%
Middle rise (12 m ~ 25 m)	High density (HRHD)	above 35%
	Middle density (HRMD)	20 ~ 35%
	Low density (HRLD)	below 20%
Low rise (below 12 m)	High density (HRHD)	above 35%
	Middle density (HRMD)	20 ~ 35%
	Low density (HRLD)	below 20%

**11.2 Statistical modelling method**

Usually the measurement data are very limited and not comprehensive. Therefore, for specific morphologies and specific operating frequencies, the following method can be used to derive the parameters for the MIMO channel model. Measurements of channel characteristics for 9 typical morphologies at 3.705 GHz have shown good statistical agreement when compared against modelling method.

Models are defined for the situation of  $h_b > h_r$ . Definitions of the parameters  $f$ ,  $d$ ,  $h_r$ ,  $h_b$ ,  $\Delta h_b$  and  $h_m$  are described in § 3.1, and  $B_d$  represents building density. The path morphology approach is valid for:

- $f$ : 800 to 6 000 MHz
- $d$ : 100 to 800 m
- $h_r$ : 3 to 60 m
- $h_b$ :  $h_r + \Delta h_b$
- $\Delta h_b$ : up to 20 m
- $h_m$ : 1 to 3 m
- $B_d$ : 10 to 45%

In the statistical modelling, the buildings are generated in a fully random fashion. It is well known that the distribution of building height  $h$  is well fitted statistically by Rayleigh distribution  $P(h)$  with the parameter  $\mu$ .

$$P(h) = \frac{h}{\mu^2} \exp\left(-\frac{h^2}{2\mu^2}\right) \quad (67)$$

To derive the statistical parameters of Rayleigh distribution for given morphology, the use of available GIS database is recommended. For the horizontal positions of buildings, it can be assumed to be uniformly distributed.

The wave-propagation calculation is performed for each realization of building distribution using the ray tracing method. 15 times reflection and 2 times diffraction are recommended for simulation. Penetration through buildings are also important. It is recommended to set up the receiving power threshold properly to consider the building penetration. To obtain the model parameters, simulations

should be performed for enough number of realizations for each morphology. At least 4 times realization is recommended. For each realization, enough number of receivers should be put in the calculation region, in order to obtain statistically meaningful data. It is recommended that at least 50 receivers are available at each 10 m sub-interval of distance. The transmitting antenna height and the receiving antenna should be set at the appropriate values. It is recommended that the values of dielectric constant and conductivity are set at  $\epsilon_r = 7.0$ ,  $\sigma = 0.015$  S/m for buildings, and  $\epsilon_r = 2.6$ ,  $\sigma = 0.012$  S/m for grounds.

The parameter values of building height distribution for typical cases are given in Table 18. Building sizes are  $30 \times 20$  m<sup>2</sup>,  $25 \times 20$  m<sup>2</sup>, and  $20 \times 20$  m<sup>2</sup> for high, middle and low rise. Building densities are 40%, 30%, and 20% for high, middle and low density.

TABLE 18

**Parameters of building height distribution for statistical modelling**

Path morphology	Rayleigh parameter $\mu$	Range of building height distribution (m)	Average building height (m)
HRHD	18	12.3~78.6	34.8
HRMD		12.5~70.8	34.4
HRLD		13.2~68.0	34.2
MRHD	10	7.3~41.2	19.5
MRMD		7.2~39.0	19.6
MRLD		7.4~40.4	19.4
LRHD	6	2.1~23.1	9.1
LRMD		2.5~22.2	9.4
LRLD		2.5~23.5	9.5

### 11.3 Path loss model

The path loss model in this recommendation is given by:

$$PL = PL_0 + 10 \cdot n \cdot \log_{10}(d) + S \quad (\text{dB}) \quad (68)$$

$$PL_0 = -27.5 + 20 \cdot \log_{10}(f) \quad (\text{dB}) \quad (69)$$

where  $n$  is the path loss exponent.  $S$  is a random variable representing the random scatter around the regression line with normal distribution, and the standard deviation of  $S$  is denoted as  $\sigma_s$ . The units of  $f$  and  $d$  are MHz and metres, respectively.

The path loss parameters for typical cases of 9 path morphologies from statistical modelling at 3.705 GHz are summarized in Table 19. The values in the Table are fitted for all receivers at the height of 2 m located along the path at distances from 100 m to 800 m.

TABLE 19

## Path loss parameters for 9 path morphologies at 3.705 GHz

Path morphology	Transmitting antenna height (m)	Average building density (%)	$n$	$\sigma_s$
HRHD	50	40	3.3	9.3
HRMD	50	30	2.9	6.3
HRLD	50	20	2.5	3.6
MRHD	30	40	2.8	4.7
MRMD	30	30	2.6	4.9
MRLD	30	20	2.3	2.7
LRHD	20	40	2.4	1.3
LRMD	20	30	2.3	1.8
LRLD	20	20	2.2	1.8

## 11.4 Delay spread model

The r.m.s. delay spread can also be modelled as a function of distance. The r.m.s. delay spread along NLoS-dominant paths at distances from 100 m to 800 m can be modelled as a distance-dependent model given by:

$$DS = A \cdot d^B \quad (\text{nsec}) \quad (70)$$

The delay spread parameters for typical cases of 9 path morphologies from statistical modelling at 3.705 GHz are summarized in Table 20. The receiver heights are 2 m, and outliers are properly removed to obtain the fitted parameters.

TABLE 20

## Delay spread parameters for 9 path morphologies at 3.705 GHz

Path morphology	Transmitting antenna height (m)	Average building density (%)	Delay spread (nsec)	
			$A$	$B$
HRHD	50	40	237	0.072
HRMD	50	30	258	0.074
HRLD	50	20	256	0.11
MRHD	30	40	224	0.095
MRMD	30	30	196	0.12
MRLD	30	20	172	0.19
LRHD	20	40	163	0.18
LRMD	20	30	116	0.23
LRLD	20	20	90	0.29



### 11.5 Angular spread model

The angular spread of departure (ASD) and arrival (ASA) along the paths at distances from 100 m to 800 m can be modelled as a distance-dependent model given by:

$$ASD = \alpha \cdot d^{\beta} \quad (\text{degrees}) \quad (71)$$

$$ASA = \gamma \cdot d^{\delta} \quad (\text{degrees}) \quad (72)$$

The parameters of ASD and ASA for typical cases of 9 path morphologies from statistical modelling at 3.705 GHz are summarized in Table 21 and Table 22.

TABLE 21

ASD parameters for 9 path morphologies at 3.705 GHz

Path morphology	Transmitting antenna height (m)	Average building density (%)	$\alpha$	$\beta$
HRHD	50	40	107	-0.13
HRMD	50	30	116	-0.18
HRLD	50	20	250	-0.31
MRHD	30	40	115	-0.22
MRMD	30	30	232	-0.33
MRLD	30	20	264	-0.37
LRHD	20	40	192	-0.33
LRMD	20	30	141	-0.29
LRLD	20	20	113	-0.24

TABLE 22

ASA parameters for 9 path morphologies at 3.705 GHz

Path morphology	Transmitting antenna height (m)	Average building density (%)	$\gamma$	$\delta$
HRHD	50	40	214	-0.27
HRMD	50	30	147	-0.17
HRLD	50	20	140	-0.14
MRHD	30	40	127	-0.15
MRMD	30	30	143	-0.16
MRLD	30	20	132	-0.13
LRHD	20	40	109	-0.09
LRMD	20	30	124	-0.11
LRLD	20	20	94	-0.06