

RECOMMENDATION ITU-R P.1411

**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)

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 Recommendations ITU-R P.370 and ITU-R P.529 provide 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	<ul style="list-style-type: none"> – 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	<ul style="list-style-type: none"> – 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	<ul style="list-style-type: none"> – Single and double story dwellings – Roads are generally two lanes wide with cars parked along sides – Heavy to light foliage possible – Motor traffic usually light
Rural	<ul style="list-style-type: none"> – 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	Velocity for vehicular users
Urban high-rise	1.5 m/s	Typical downtown speeds around 50 km/h (14 m/s)
Urban/suburban low-rise	1.5 m/s	Around 50 km/h (14 m/s) Expressways up to 100 km/h (28 m/s)
Residential	1.5 m/s	Around 40 km/h (11 m/s)
Rural	1.5 m/s	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 km 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 m to 500 m	Outdoor; mounted below average roof-top level
Pico-cell	Up to 100 m	Indoor or outdoor (mounted below roof-top level)

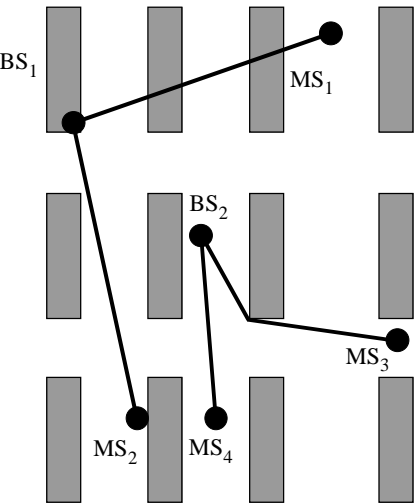
(Note that although the “small macro-cell” category is given an upper limit of 3 km, this Recommendation is intended for distances up to 1 km.)

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 BS₁ 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 BS₂ 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 BS₂ may be used.

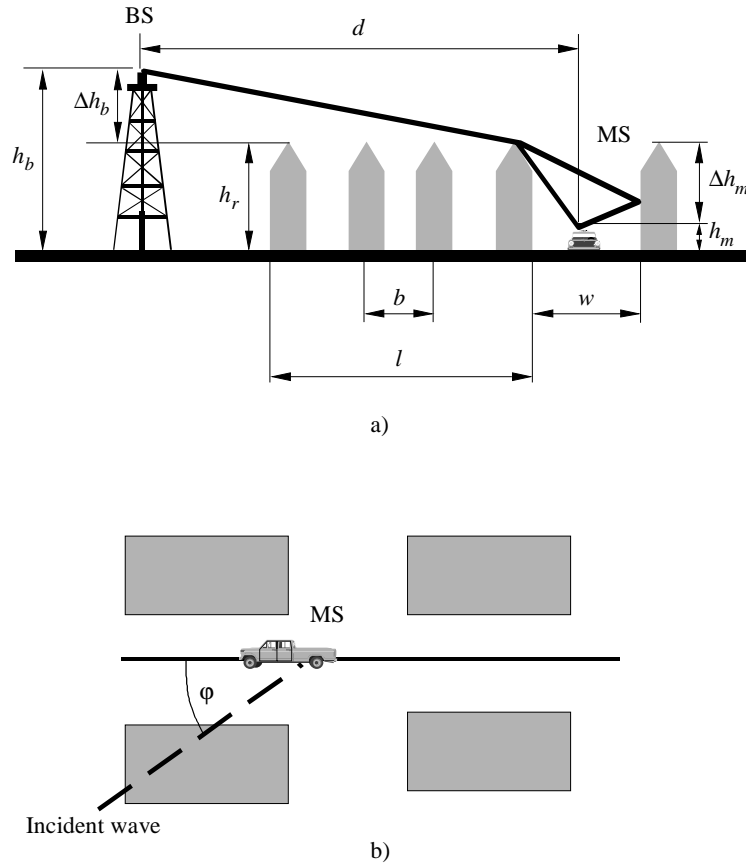
FIGURE 1
Typical propagation situations in urban areas



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

The typical NLOS case (link BS₁-MS₁ 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



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The relevant parameters for this situation are:

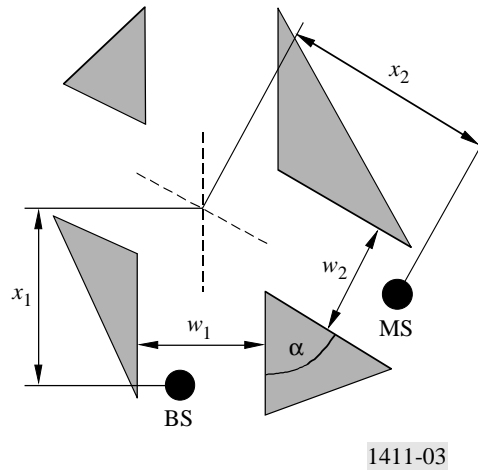
- h_r : average height of buildings (m)
- w : street width (m)
- b : average building separation (m)
- ϕ : street orientation with respect to the direct path (degrees)
- h_b : BS antenna height (m)
- h_m : MS antenna height (m)
- l : length of the path covered by buildings (m)
- d : distance from BS 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 BS₂-MS₃ 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)
- 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 BS₁-MS₂ and BS₂-MS₄ 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 λ is the wavelength (m).

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:

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

Millimetre-wave propagation

At frequencies above 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 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

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 base station antenna height, while L_{msd} is dependent on whether the base station antenna is at, below or above building heights.

$$L_{NLOS1} = \begin{cases} L_{bf} + L_{rts} + L_{msd} & \text{for } L_{rts} + L_{msd} > 0 \\ L_{bf} & \text{for } L_{rts} + L_{msd} \leq 0 \end{cases} \quad (5)$$

The free-space loss is given by:

$$L_{bf} = 32.4 + 20 \log_{10} (d / 1000) + 20 \log_{10} (f) \quad (6)$$

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.

$$L_{rts} = -16.9 - 10 \log_{10}(w) + 10 \log_{10}(f) + 20 \log_{10}(\Delta h_m) + L_{ori} \quad (7)$$

$$L_{ori} = \begin{cases} -10 + 0.354\phi & \text{for } 0^\circ \leq \phi < 35^\circ \\ 2.5 + 0.075(\phi - 35) & \text{for } 35^\circ \leq \phi < 55^\circ \\ 4.0 - 0.114(\phi - 55) & \text{for } 55^\circ \leq \phi \leq 90^\circ \end{cases} \quad (8)$$

where:

$$\Delta h_m = h_r - h_m \quad (9)$$

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 :

$$d_s = \frac{\lambda d^2}{\Delta h_b^2} \quad (10)$$

where (see Fig. 2a)):

$$\Delta h_b = h_b - h_r \quad (11)$$

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 $l \gg d_s$.)

$$L_{msd} = L_{bsh} + k_a + k_d \log_{10}(d/1000) + k_f \log_{10}(f) - 9 \log_{10}(b) \quad (12)$$

where:

$$L_{bsh} = \begin{cases} -18 \log_{10}(1 + \Delta h_b) & \text{for } h_b > h_r \\ 0 & \text{for } h_b \leq h_r \end{cases} \quad (13)$$

is a loss term that depends on the base station height,

$$k_a = \begin{cases} 54 & \text{for } h_b > h_r \\ 54 - 0.8\Delta h_b & \text{for } h_b \leq h_r \text{ and } d \geq 500 \text{ m} \\ 54 - 1.6\Delta h_b d/1000 & \text{for } h_b \leq h_r \text{ and } d < 500 \text{ m} \end{cases} \quad (14)$$

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

$$k_f = \begin{cases} 0.7(f/925 - 1) & \text{for medium sized city and suburban} \\ & \text{centres with medium tree density} \\ 1.5(f/925 - 1) & \text{for metropolitan centres} \end{cases} \quad (16)$$

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 base station and the rooftops.

$$L_{msd} = -10 \log_{10} (Q_M^2) \quad (17)$$

where:

$$Q_M = \begin{cases} 2.35 \left(\frac{\Delta h_b}{d} \sqrt{\frac{b}{\lambda}} \right)^{0.9} & \text{for } h_b > h_r \\ \frac{b}{d} & \text{for } h_b \approx h_r \\ \frac{b}{2\pi d} \sqrt{\frac{\lambda}{\rho}} \left(\frac{1}{\theta} - \frac{1}{2\pi + \theta} \right) & \text{for } h_b < h_r \end{cases} \quad (18)$$

and

$$\theta = \arctan \left(\frac{\Delta h_b}{b} \right) \quad (19)$$

$$\rho = \sqrt{\Delta h_b^2 + b^2} \quad (20)$$

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).

$$L_{NLOS2} = -10 \log_{10} \left(10^{L_r/10} + 10^{L_d/10} \right) \quad \text{dB} \quad (21)$$

where:

L_r : reflection path loss defined by:

$$L_r = -20 \log_{10} (x_1 + x_2) + x_2 x_1 \frac{f(\alpha)}{W_1 W_2} - 20 \log_{10} \left(\frac{4\pi}{\lambda} \right) \quad \text{dB} \quad (22)$$

where:

$$f(\alpha) = \begin{cases} -41 + 110\alpha & \text{for } \alpha \leq 0.33 \\ -13.94 + 28\alpha & \text{for } 0.33 < \alpha \leq 0.42 \\ -5.33 + 7.51\alpha & \text{for } 0.42 < \alpha \leq 0.71 \\ 0 & \text{for } \alpha > 0.71 \end{cases} \quad (23)$$

L_d : diffraction path loss defined by:

$$L_d = -10 \log_{10} [x_2 x_1 (x_1 + x_2)] + 2D_a + 0.1 \left(90 - \alpha \frac{180}{\pi} \right) - 20 \log_{10} \left(\frac{4\pi}{\lambda} \right) \quad \text{dB} \quad (24)$$

$$D_a \approx - \left(\frac{40}{2\pi} \right) \left[\arctan \left(\frac{x_2}{w_2} \right) + \arctan \left(\frac{x_1}{w_1} \right) - \frac{\pi}{2} \right] \quad (25)$$

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:

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

$$\begin{aligned} \text{roof-height} &= 3 \text{ m for pitched roofs} \\ &= 0 \text{ m for flat roofs} \end{aligned}$$

$$w = b/2$$

$$b = 20 \text{ to } 50 \text{ m}$$

$$\phi = 90^\circ$$

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 may be determined by comparing signal levels outside and inside the building at the same height. 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 4 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 4

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		

6 Multipath models

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

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 2.5 GHz at distances from 50 to 400 m. The delay spread S at distance of d m follows a normal distribution with the mean value given by:

$$a_S = 99.35 \log(d + 13.24) \quad \text{ns} \quad (26)$$

and the standard deviation given by:

$$\sigma_S = 39.90 \log(d) - 27.67 \quad \text{ns} \quad (27)$$

The average shape of the delay profile was found to be:

$$P(t) = P_0 + 50 \left(e^{-t/\tau} - 1 \right) \quad \text{dB} \quad (28)$$

where:

P_0 : peak power (dB)

τ : decay factor

and t is in nanoseconds.

From the measured data, for a delay spread S , τ can be estimated as:

$$\tau = 4.0 S + 266.0 \quad \text{ns} \quad (29)$$

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.)
