# RECOMMENDATION ITU-R P.1406-1

## Propagation effects relating to terrestrial land mobile and broadcasting services in the VHF and UHF bands

(Question ITU-R 203/3)

(1999-2007)

**Scope**

This Recommendation provides information on various aspects of propagation which are likely to affect the terrestrial land mobile and broadcasting services. These aspects should be taken into account in the design and planning of such services.

The ITU Radiocommunication Assembly,

*considering*

a) that there is a need for information on aspects of propagation likely to affect terrestrial land mobile and broadcasting services,

*recommends*

**1** that the information contained in Annex 1 should be taken into account in the design and planning of such services.

## Annex 1

### Introduction

This Recommendation provides information on various aspects of propagation which are likely to affect the terrestrial land mobile and broadcasting services. These aspects should be taken into account in the design and planning of such services.

### 2 Attenuation due to land cover

These losses are likely to be of great importance for the land mobile service. They will depend on the category of the terrain, the extent of vegetation, and on the location, density and height of buildings. Table 1 summarizes the applicability of the various available ITU-R Recommendations:

TABLE 1

**Recommendations discussing land cover**

| ITU-R P. | Applicability |
|---|---|
| 1546 | Antenna height corrections |
| 452 | Clutter losses |
| 833 | Attenuation in vegetation (especially trees) |
| 1058 | Terrain databases |
| 1146 | Antenna height corrections |
| 1812 | Vegetation and clutter losses |

## 3 Signal strength variability

### 3.1 General

The strength of the signal received will vary with both time and location. The signal may be composed of direct, diffracted, reflected, and refracted components. The quality of the reception will depend upon several factors such as the receiving environment, frequency shifts, time delays, and type of modulation. Similarly, unwanted transmissions may also be received from other sources sharing the same frequencies as, or adjacent frequencies to, the wanted signal. These, too, will have to be taken into account in assessing the quality of service. These unwanted transmitters may be so distant from the receiver that the extent of the temporal variation created by the various forms of abnormal propagation will need to be quantified. This may involve a situation in which the risk of interference has to be accepted for a defined percentage of time at various receiving locations in order to allow the network(s) to operate.

In summary, the assessment of reception and the definition of the service area involve the analysis of wanted and unwanted signals in both time and location domains, and the extent of the correlation between them.

### 3.2 Fading regimes

A reduction in signal strength occurs when the receiver is in the shadow of trees or buildings or of terrain obstacles or other objects. The signal then arrives at the receiver after being diffracted over or around these obstacles, or being reflected from other objects. If the size and shape of the obstacles are known, an attempt can be made to calculate from theory the additional path loss that they create. Otherwise, if only general information about the environment is available, an estimate of path loss can be made from measurements made in similar situations. In any case, on a sufficiently small scale, a theoretical estimate will not be possible, and an estimate based on measurements will be necessary. Such an estimate must be statistical in nature. Typically, it consists of a median path loss for a specified area, and a measure of its variance.

The signal may vary explicitly with time because of atmospheric variations, but over distances of less than about 50 km, this kind of variation is relatively unimportant. More important in the land mobile service is spatial variability, which is seen as time variability by a moving receiver.

It is convenient to divide spatial variability into two regimes, rapid fading due to multipath, which occurs on the scale of a few wavelengths, and slower fading due to changes in shadowing. In analysing measurements, the two can be separated in the following way: a number of measurements should be made at equal intervals over a distance of about 40 wavelengths, and a median signal level or path loss found for this distance. About 36 such measurements are required to obtain a median accurate to within 1 dB with 90% probability. The distance between measurements should be at least 0.8 of a wavelength in order for adjacent measurements to be uncorrelated, a criterion that is satisfied with the conditions just given. This procedure is repeated for other distance intervals of 40 wavelengths until the area of interest is covered. Experience has shown that the distribution of these median values will be log-normal, and therefore their distribution can be characterized by their mean or median, and their standard deviation. This is the distribution of signal strength variations due to shadowing, with the multipath variation removed.

#### 3.2.1 Shadowing

A number of measurements have been made of signal-strength distribution due to shadowing. It is important to specify whether the area of interest is a large one, i.e. all paths of a given length around a base transmitter or all paths of a given length in a geographical region; or a small one, i.e. an area of dimensions of a few hundred metres over which the path profile and the general environment of the receiver do not change significantly. The signal variability will be greater in a large area than in a small one.

In rural areas, for all paths of a given length the standard deviation, $\sigma_L$, of the location variability distribution may be estimated by:

$$\begin{aligned} \sigma_L &= 6 + 0.69\left(\frac{\Delta h}{\lambda}\right)^{1/2} - 0.0063\left(\frac{\Delta h}{\lambda}\right) \quad \text{dB} \quad \text{for } \Delta h/\lambda < 3\,000 \\ \sigma_L &= 25 \quad \text{dB} \quad \text{for } \Delta h/\lambda > 3\,000 \end{aligned} \tag{1}$$

where:

$\Delta h$: interdecile height variation (m)

$\lambda$: wavelength (m)

$\lambda$ $= 300/f$

$f$: frequency (MHz).

In flat urban areas, the standard deviation over a large area may be estimated by:

$$\sigma_L = 5.25 + 0.42 \log (f/100) + 1.01 \log^2 (f/100) \qquad \text{dB} \tag{2}$$

valid from 100 MHz to 3 000 MHz.

The standard deviation of location variability over small areas is less well-known. It is thought to depend on land cover, but it is not clear what that dependence is. There is some evidence that the standard deviation decreases with increasing distance from the transmitter, but this is not always clear. A formula (3) roughly summarizes some measurements at UHF for distances up to 50 km and all types of land cover, and which retains the frequency dependence of the formula (2), is:

$$\sigma_L = 2.7 + 0.42 \log (f/100) + 1.01 \log^2 (f/100) \qquad \text{dB} \tag{3}$$

A different empirical expression for such shadow fading is given in Recommendation ITU-R P.1546.

### 3.2.2 Multipath fading

On a scale of a few wavelengths, signal variability is determined by multipath effects. As a minimum, it is to be expected that a ground reflected component will be present, and as a consequence, multipath effects are always observed in practice. Such multipath effects generally lead to the classification of a channel as being "Rayleigh" or "Ricean".

In the former case the received signal is the sum of many independently fading components, and can be represented by the Rayleigh distribution (see Recommendation ITU-R P.1057). Such a channel would be typical for a narrow band cellular mobile service operating in a cluttered urban environment, with no line-of-sight to the transmitter.

The Ricean channel is associated with the situation where one of the components of the received signal, such as that associated with a line-of-sight path to the transmitter, has a power that is constant on the timescale of the multipath fading. In this case, the overall signal fading can be modelled by the Nakagami-Rice distribution (see Recommendation ITU-R P.1057). This distribution is often formulated in terms of the parameter, $K$ (the "Rice factor") which is defined as the ratio between the power in the constant part of the signal and that in the random part. For $K = 0$, the distribution becomes Rayleigh.

### 3.3 Local reflections

Radiowaves arriving at a mobile receiver may be reflected from the ground and from nearby objects such as buildings, trees and vehicles. The ground-reflected wave is coherent with the direct wave and causes the received signal to vary with receiver antenna height. However, waves reflected from nearby objects have random amplitudes and phases.

Constructive and destructive interference between the direct and various reflected waves creates an interference pattern in which the distance between minima is at least one half wavelength.

In urban or forested areas, there are many reflected waves, and the instantaneous field strength when measured over distances of a few tens of wavelengths follows approximately a Rayleigh distribution.

The interference pattern gives rise to fast fading in a moving receiver, and reflections from moving vehicles can cause fading even in a stationary receiver.

Fades of 30 dB or more below the mean level are common.

Local reflections can also have the beneficial effect of filling in deep shadows to some degree.

### 3.4 Signal correlation

The correlation in mean received power from different sources is important for the evaluations of carrier to interference ratio, $C/I$.

Consider $C$ as the desired carrier power (dB) with a mean $C_m$ and a standard deviation $\sigma_C$ and $I$ as the power (dB) from one interfering source with a mean $I_m$ and a standard deviation $\sigma_I$ then the mean $C/I$-ratio $(C/I)_m$, becomes:

$$(C/I)_m = C_m - I_m \qquad \text{dB} \tag{4}$$

which is independent of the correlation.

The standard deviation of the $C/I$ ratio, $\sigma_{C/I}$, becomes:

$$\sigma_{C/I} = \sqrt{\sigma_C^2 + \sigma_I^2 - 2\rho\sigma_C\sigma_I} \tag{5}$$

where $\rho$ is the correlation coefficient. In the case of $\sigma = \sigma_I = \sigma_C$, equation (5) simplifies to:

$$\sigma_{C/I} = \sigma \sqrt{2(1-\rho)} \tag{6}$$

The correlation coefficients derived from sample sets of received power data indicate that for reception from opposite directions no significant correlation is evident. When the angle of arrival difference at the mobile is small, significant correlations exist. Typical values of $\rho$ for co-sited sources are 0.8 to 0.9 in farmed and heavily wooded areas. In metropolitan areas the correlation is generally lower ($\rho$ between 0.4 and 0.8). Usually correlations in mountainous areas are very low. However, values of $\rho > 0.8$ are observed in exceptional situations even in mountainous areas.

## 4 Delay spread

Many types of radio system, particularly those using digital techniques, are sensitive to multipath propagation introduced to the signal by the path characteristics. After the arrival of the direct signal, a number of reflected signals arrive causing this phenomenon. Based on the amplitudes and time delays of these signals a channel impulse response (CIR) can be derived. Several parameters describing the propagation channel can be extracted from the CIR, see Recommendation ITU-R P.1407.

One of the important parameters is r.m.s. delay spread, $S$, as given in equations (3) and (4) of Recommendation ITU-R P.1407. A useful measure of the extent of time spread is the multipath delay spread, $T_m$, where:

$$T_m = 2\,S \tag{7}$$

Which of the parameters discussed above are most useful in predicting system performance is dependent upon the particular modulation scheme involved.

### 4.1 Impact on system performance

Depending on the ratio between delay spread and symbol duration, different phenomena are responsible for the bit error ratio. Multipath signals yield a rapid phase variation in space and frequency. For modulation schemes using some sort of angular modulation, e. g. differential phase shift keying (DPSK), these phase variations are responsible for the so-called irreducible errors, which remain, even at large signal-to-noise ratios. As long as the delay spread is smaller than the symbol duration, the irreducible errors depend more on the delay spread than on the exact shape of the impulse response. However, if the delay spread exceeds the symbol duration, intersymbol interference occurs, which depends more on the CIR shape.

### 4.2 Delayed signals due to local scatterers

Signals with short delays are often observed in areas with a uniform distribution of local scatterers. Such signals typically occur in urban or suburban areas, where no line-of-sight situations to large reflectors at longer distances (mountains, hills) exist. The uniform distribution of the scattered signals usually yields homogeneous impulse responses, (see also Recommendation ITU-R P.1238). In addition to the homogeneous portion of the impulse response, strong echoes from large buildings are sometimes identified resulting in an inhomogeneous impulse response. Furthermore, inhomogeneous impulse responses are observed at street intersections.

Typical values of r.m.s. delay spread observed in urban and suburban areas are in the range of 0.8 μs to 3 μs. For high-data rate systems a more detailed knowledge of the impulse response may be necessary. The corresponding detailed signal strength calculation for the multipath signals incorporates ray-tracing or ray-launching techniques in conjunction with the application of high-resolution building data.

### 4.3 Delayed signals due to large distant scatterers

Signals with long delays typically occur in areas where mountains near to a flat area, such as a plain or a valley. This effect is particularly evident where there is a large flat area adjacent to a single range of mountains, reducing the possible mitigating effects of other mountain ranges. Typical values have been observed up to about 25 μs.

The strength of the direct signal should be calculated by the appropriate method, as determined by Recommendation ITU-R P.1144 over the limits of validity defined in that Recommendation. The strength of reflected signals can be calculated from the formula (8):

$$P_{rs} = \frac{P_t G_t G_r}{32\pi^3} \left( \frac{\lambda}{r_1 r_2} \right)^2 \Gamma A \cdot \cos\,\theta_1 \cdot \cos\,\theta_2 \tag{8}$$

where:

$P_{rs}$: power of the received signal

$P_t$: transmitter power output

$G_t$: effective transmitter antenna gain (including line- and filtering-losses)

$G_r$: effective receiver antenna gain (including line- and filtering-losses)

$\lambda$: wavelength in the same units as $r_1$ and $r_2$

$r_1$, $r_2$: distances from the scattering plane (mountain surface) to the transmitter and to the receiver

$\Gamma$: reflectivity of the scattering plane

$A$: area of the scattering plane in same units (squared) as $r_1$ and $r_2$

$\theta_1$, $\theta_2$: acute angles that the normal to the scattering plane makes with the rays to the transmitter and to the receiver.

The above formula (8) does not consider the vertical angle but it should be sufficiently accurate for land mobile work. It should also be pointed out that this formula will be less accurate in the presence of ducts and other refractive phenomena. In extreme cases it may not be applicable at all because a reflector that would normally be considered is no longer within radio line-of-sight or, conversely, where a mountain side that is normally outside line-of-sight is brought into line-of sight.

For simplicity and speed of calculation, each mountain range is considered to be a single scattering plane with the same azimuthal orientation as that of the crest of the range. The area, $A$, is the area of the portion of the range that is within the half-power antenna beamwidths of both the transmitting and receiving antennas and is not shadowed from either antenna. The parameters $r_1$, $r_2$, $\theta_1$, and $\theta_2$ are calculated from the centre of the aforementioned portion of the mountain range.

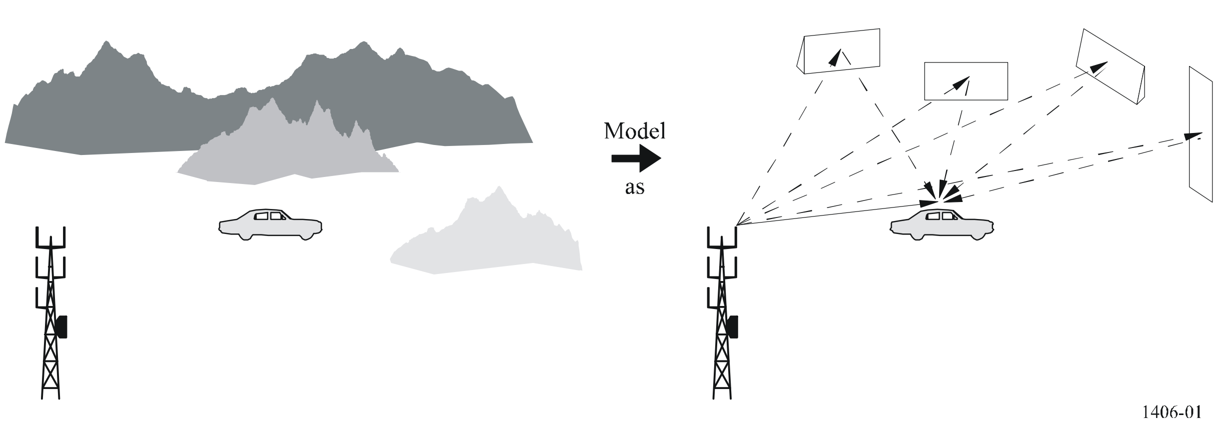
If a portion of a reflecting mountain range is shadowed from either the transmitting or receiving station by a closer mountain range such that the reflective area of the farther range is separated into sections, the calculation is done by considering the unshadowed portions as separate mountain ranges. This concept is shown in Fig. 1.

The reflectivity, $\Gamma$, has been observed to have values between 0.001 and 0.2 (–30 dB and –7 dB). For forested mountains, the reflectivity is unlikely to exceed 0.05 (–13 dB). For bare mountains, the reflectivity would be unlikely to exceed 0.2 (–7 dB).

Any clutter losses applied to the direct signal calculation should also be applied to the reflected signal calculation.

FIGURE 1

**Modeling of direct and reflected signals**



# 5 Antenna effects

## 5.1 Polarization effects

### 5.1.1 Depolarization phenomena in the land mobile environment

In the land mobile environment some or all of the transmitted energy may be scattered out of the original polarization due to diffraction and reflection of the radiowave. It is convenient to take this depolarization effect into consideration by using a cross-polarization discrimination (XPD) factor, as defined in Recommendation ITU-R P.310.

XPD measurements at 900 MHz show that:

– XPD depends little on distance;

– the average XPD in urban and residential areas ranges from 5 dB to 8 dB, and is over 10 dB in open areas;

– the average correlation between vertical and horizontal polarization is 0.

XPD increases with decreasing frequency, to about 18 dB at 35 MHz.

XPD is log-normally distributed with a standard deviation somewhat dependent on the frequency. The average value of the difference between the 10% and 90% values (in the frequency range 30 MHz to 1 000 MHz) is about 15 dB. Whether the original polarization is vertical or horizontal has been observed to make only a slight difference in this respect.

Two types of time variation of the depolarization effect have been found. The first is a slow variation resulting from the changing electrical properties of the ground with weather conditions. This effect is most pronounced at lower frequencies. The second is due to the motion of trees which gives a depolarization fading phenomenon amounting to several decibels in amplitude at quite moderate wind velocities.

### 5.1.2 Polarization diversity

Because of the considerable amount of scattering in urban and residential areas, and the consequent low values of XPD, polarization diversity may be a useful technique for improving reception. The most basic option would be the use of two orthogonal linear polarizations at the base station.

As an alternative to diversity, circular polarization at the base station and linear polarization at the mobile terminal, while resulting in a 3 dB polarization mismatch, can take advantage of the depolarization due to scattering and provide a more constant received signal level in the mobile environment.

## 5.2 Height gain: base and mobile

Height gain refers to a change in received signal strength with antenna height. Although usually increasing with height (positive height gain), it can also decrease with height (negative height gain). In the absence of local clutter, the direct signal can interact with a ground reflected ray from the same transmitter. The resulting field strength variation, in a vertical direction, is a series of maxima and minima as the path geometry causes the two signals to go in and out of phase.

In practice, particularly with mobile receivers, clutter and other reflected signals tend to minimize this two-ray effect and above 200 MHz it can be neglected in most situations. Instead, it is usually found that raising the antenna simply reduces the effective clutter loss causing the received signal to increase with height. Since antenna height is related to clutter loss in this way, this form of height gain can be categorized in terms of the type of ground cover as in Recommendation ITU-R P.370. In other prediction methods, especially those which use a terrain data base, antenna height is frequently linked directly to the calculation of clutter loss.

For base stations, operating at frequencies below 200 MHz and located in open areas, 2-ray effects can sometimes be found so that re-positioning of the antenna may be required to avoid negative height gain. Such an effect is difficult to predict precisely, since a detailed knowledge of the terrain profile at the reflection point is required. Above 200 MHz, due to the smaller wavelength, this particular problem tends to diminish and at UHF and above it can be ignored.

### 5.3 Correlation/space diversity

Space diversity is practical for antennas having cross-correlations up to about 0.7. In general, this makes portable and mobile diversity reception nearly impractical. For the base station case, however, a number of techniques are possible for reducing the cross-correlation between antennas. The two most practical are vertical and horizontal separation.

To reduce the cross-correlation to 0.7 or less, vertically spaced antennas must be separated by approximately 17 wavelengths or more. Horizontal separation can be more effective, depending upon the relative orientations of the plane of the antennas versus the direction of motion of the mobile. If the vertical plane through the antennas is perpendicular to the direction of motion of the mobiles, the cross-correlation will be approximately the same as that for the vertical separation case. With optimum orientation, horizontal antennas can be separated by as little as 8 wavelengths. It should be borne in mind that nearly optimal orientations can be maintained only in special cases, such as systems using sectored antennas.

### 5.4 Realisable vehicular mobile antenna gain

Since vehicular mobile stations usually operate in a multipath environment, it is not surprising that mobile antenna gain will not, in most cases, match that measured on the pattern range. Additionally, even in line-of-sight non-multipath conditions, the vertical angle of arrival is not necessarily horizontal. In fact, practical cases exist where the vertical angle of arrival can exceed 10°. In the latter case, the vertical angle of arrival could easily be on a null or a minor lobe, rather than the main lobe of the mobile antenna’s vertical pattern.

Tests measuring mobile antennas rated at 3 dB and 5 dB gain relative to a $\lambda/4$ vertical monopole in practical situations have shown that their practical gain values rarely meet the values measured on an antenna range. In multipath situations or in clear situations with high angles of arrival (>2°), the practical gain of either antenna is approximately 1.5 dB relative to a $\lambda/4$ vertical monopole over a distance range up to at least 55 km. In clear situations with low elevation angles, full gain may be realisable.

## 6 Portable effects

### 6.1 Building entry loss

Losses due to penetration into buildings have been defined as the difference between the signal measured outside at street level and that measured inside the building. In this section it is only intended to cover the loss due to the building structure. Once inside a building further losses can be incurred due to its internal construction and contents, and this aspect is dealt with in Recommendation ITU-R P.1238.

Propagation losses incurred through entering a building can vary considerably depending on the type of building and the construction materials. The frequency of the signal and its angle of incidence are also significant. Consequently, loss values can range from a few to many tens of decibels.

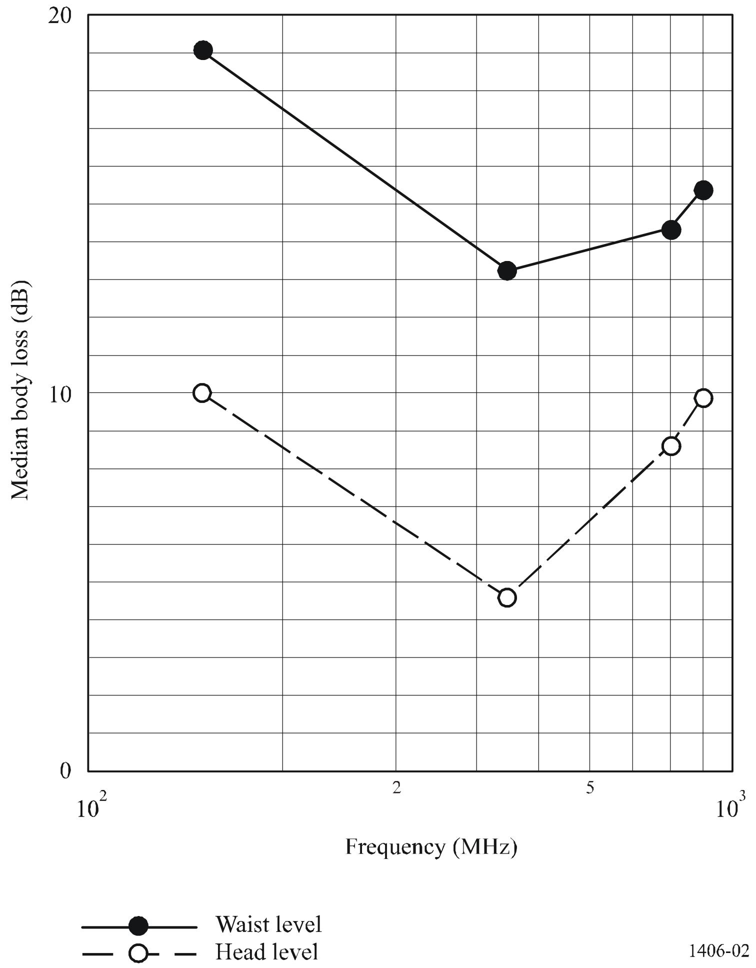
These losses are being investigated in detail by several organizations. It may be that, eventually, a range of building sub-categories will be defined, each with its own representative loss statistics.

## 6.2 Body loss

The presence of the human body in the field surrounding a portable transceiver, cellular phone, or paging receiver can degrade the effective antenna performance – the closer the antenna to the body the greater the degradation. The effect is also frequency dependent as shown in Fig. 2, which is based on a recent detailed study on portable transceivers at four commonly used frequencies.

FIGURE 2

**Typical body loss - Portable transceiver**




It is not possible to talk exclusively of “body loss” when dealing with paging receivers because a paging receiver’s antenna is integral to the unit. For that reason, the sensitivity of a paging receiver is typically specified in terms of field strength (usually in μV/m). It is, however, useful to know how much antenna gain is provided by a typical integral antenna when the pager is worn on the hip. Table 2 shows those values for a particular pager at three different frequencies.

TABLE 2

**Paging receiver gain**

| Frequency (MHz) | Antenna Gain (dB) |
|---|---|
| 160 | –25 |
| 460 | –22 |
| 930 | –19 |

## 7 Guided propagation

Propagation can be viewed as “guided” whenever a wavefront is not free to expand in three dimensions. Examples include tropospheric ducting, “street-canyon” communications, and transmission-line technology, particularly waveguides.

Section 7.1 discusses propagation along tunnels which needs to be considered when a radio signal enters at either end or is launched by an antenna within the tunnel. Section 7.2 discusses the closely related topic of leaky feeders.

### 7.1 Propagation in tunnels

Radio systems are typically required in road and rail tunnels for broadcasting and mobile telephone services, and in mines or other underground facilities for safety and operational reasons.

Propagation within a tunnel having some degree of regularity can be interpreted in terms of waveguide theory. Depending on frequency, radiowaves will travel along the length of the tunnel in transverse-electrical (TE) or transverse-magnetic (TM) modes, in which the electrical or magnetic components, respectively, are only transverse to the tunnel axis. Every mode has a critical frequency below which it will not propagate. Above its critical frequency each mode propagates with its own propagation and phase coefficients. The mode with the lowest frequency defines the waveguide cut-off frequency, below which no practical propagation exists. For a rectangular waveguide, the cut-off frequency is equivalent to a wavelength of twice the width of the longer side. For an irregular tunnel, a useful approximation is a wavelength equal to the tunnel cross-section circumference.

For normal transport or habitable tunnels, radio services at VHF will normally be above the cut-off frequency, and at UHF well above.

At frequencies well above cut-off, propagation within a tunnel can also be interpreted in terms of ray theory, and this is generally more appropriate as the wavelength becomes very small compared to the tunnel cross-section. A tunnel with sides which are smooth compared to the wavelength will support propagation by wall reflections at grazing angles, at which most materials exhibit high reflection coefficients. Due to the large variety of reflected paths available, the result has multipath characteristics, with Rayleigh or Rician fading.

Obstructions in a tunnel will cause radiowaves well above cut-off to be scattered, in general, through large angles, and will thus interrupt the process of grazing-incidence reflections. A diffraction loss will be experienced immediately beyond an obstruction due to shadowing.

Specific attenuation rates for propagation through tunnels vary widely, and are particularly affected by irregularities and changes in tunnel direction, and obstructions, including traffic. In a typical road tunnel attenuation figures in the range 0.1 to 1 dB/m can be regarded as typical, but values outside this range can easily exist. Due to the coexistence of multiple modes above the critical frequency, attenuation rates can either increase or decrease with increasing frequency, depending on circumstances.

### 7.2 Leaky feeders

Leaky feeders are often used to overcome obstacles to propagation within a tunnel, and are often the only practical method of supporting services below cut-off, such as medium-wave broadcasting.

If the radio services to be supported are carried on a coaxial cable mounted along the tunnel length, and somewhat away from its side, and if the outer-conductor has gaps, some energy will leak through the outer-conductor as a transverse electro-magnetic (TEM)-type wave between the coaxial-outer and the tunnel walls. This process is referred to as mode-conversion. Irregularities in the coaxial-cable/tunnel system, including feeder mountings, will also cause mode-conversion. In order to control mode-conversion, some systems use sections of non-leaky feeder interspersed with discrete mode-conversion devices.

The design of leaky-feeder systems is specialized. A practical problem is that the coupling-loss between a leaky-feeder and mobile terminals is high when the feeder is mounted close to the tunnel sides, whereas clearance considerations usually prevent mounting far from a side.

## 8 Temporal variations

The received field strength will vary with time, in addition to location and the nature of the terrain.

The standard deviation of the time variability, $\sigma_t$, is given in Table 3.

TABLE 3

**Standard deviation $\sigma_t$**

| Band | | $\sigma_t$ (dB) | | | |
|---|---|---|---|---|---|
| | *d* (km) | 50 | 100 | 150 | 175 |
| VHF | Land and sea | 3 | 7 | 9 | 11 |
| UHF | Land | 2 | 5 | 7 | |
| | Sea | 9 | 14 | 20 | |

Under certain radio-meteorological conditions, the phenomenon of ducting can occur and may cause substantial signal increases leading to potential interference (see Recommendation ITU-R P.452). These effects are intermittent and short term.