RECOMMENDATION ITU-R F.1093-2*

Effects of multipath propagation on the design and operation of line-of-sight digital fixed wireless systems

(Question ITU-R 122/9)

(1994-1997-2006)

Scope

This Recommendation provides an introduction to propagation-related aspects of the design and operation of digital radio-relay systems, drawing on information from Radiocommunication Study Group 3 texts and measurements conducted by administrations. Annex 1 explains the role of multipath fading as the dominant propagation factor for digital radio-relay systems operating at frequencies below about 10 GHz. Further material discusses the roles of diversity techniques and adaptive equalization in reducing channel degradations.

The Radiocommunication Assembly,

considering

a) that fading due to multipath propagation may distort and attenuate received signals on line-of-sight paths and thereby impair the performance of fixed wireless systems (FWSs);

b) that Recommendation ITU-R P.530 provides data and methods for FWS propagation prediction and path planning;

c) that countermeasures to reduce the effects of multipath fading on system performance, such as diversity reception and adaptive equalization, are available;

d) that methods of analysing the effects of multipath fading on the error performance of FWS are needed for comparing alternative designs,

recommends

1 that multipath fading countermeasures should be incorporated in radio system design, as needed, to improve error performance;

2 that the methods in Annex 1 should be used for guidance in radio link planning.

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* This Recommendation should be brought to the attention of Radiocommunication Study Group 3.

Annex 1

Effects of multipath propagation on design and operation of line-of-sight digital FWSs

1 Introduction

The purpose of the present Annex is to furnish an introduction to propagation-related aspects of the design and operation of digital radio-relay systems, drawing on information from Radiocommunication Study Group 3 texts and measurements conducted by administrations. The first part of the Annex explains the role of multipath fading as the dominant propagation factor for digital radio-relay systems operating at frequencies below about 10 GHz. The following sections discuss the roles of diversity techniques and adaptive equalization in reducing channel degradations. Finally, the prediction of system performance depending on the foregoing factors is treated.

More detailed information on the application of the guidance contained here can be found in the Handbook on digital radio-relay systems.

2 Propagation considerations

The texts established by Radiocommunication Study Group 3 contain a wealth of information on the propagation phenomena to be taken into account in the design and operation of radio-relay systems. In particular, Recommendation ITU-R P.530 is especially concerned with “propagation data and prediction methods required for line-of-sight radio-relay systems”. In that Recommendation, the information is arranged according to the propagation effects that must be considered. The relevant meteorological information concerning the propagation mechanisms is given in other Recommendations of the P series, notably Recommendations ITU-R P.834 and ITU-R P.676.

Propagation conditions vary from month to month and from year to year, and the probability of occurrence of these conditions may vary by as much as several orders of magnitude. It may therefore take some three to five years before drawing a proper conclusion on the results of a propagation experiment. However, for system application requirements, this time is often not available and models of this variability for some parameters have been examined in Recommendation ITU-R P.841.

From propagation data it was concluded that for a well-designed path which is not subject to diffraction fading or surface reflections, multipath propagation is the dominant factor in fading below 10 GHz. Above this frequency, the effects of precipitation tend increasingly to determine the permissible path length through the system availability objectives. The necessary reduction in path length with increase in frequency, reduces the severity of multipath fading. These two principal causes of fading are normally mutually exclusive. Given the split between availability and error performance objectives, precipitation effects contribute mainly to unavailability and multipath propagation mainly to error performance. Another influence of precipitation, e.g. back-scatter from rain, may influence the choice of radio-frequency channel arrangements.

Propagation effects due to various forms of precipitation tend not to be frequency dispersive, while multipath propagation caused by tropospheric layers can be, and this may cause severe distortion of information-bearing signals. The rapid development of digital communication systems has required an improved understanding of these effects and the means to overcome them.

3 Countermeasures to propagation effects

There are two countermeasures to propagation distortion commonly used: diversity techniques and adaptive channel equalizers, which attempt to combat attenuation and distortion caused by the propagation medium. The effectiveness of a fading countermeasure is usually expressed in terms of an improvement factor. On a single test path, the improvement factor is the ratio of the outage time observed for a system without the countermeasure, to that observed when the countermeasure is operative (see Note 1). The improvement factor depends on the outage threshold chosen.

NOTE 1 – Outage time is a general term to indicate the time duration over which the system exceeds a chosen bit-error ratio (BER) threshold.

3.1 Diversity techniques

The most commonly used diversity techniques are frequency diversity and space diversity. For others, see Recommendations ITU-R F.752, ITU-R P.530 and the ITU-R Handbook on Digital Radio-Relay Systems (edition 1996).

3.1.1 Space diversity

Space diversity is one of the most effective methods of combating multipath fading. For digital radio systems, where the performance objectives can be difficult to meet owing to waveform distortions caused by multipath effects, system designs must often be based on the use of space diversity.

In space diversity systems the signals received by two vertically separated receiving antennas rarely fade simultaneously when the fades are deep. The improvement factor that a system may achieve by using these two signals depends on both propagation factors and the radio system implementation, that is, its vulnerability to the power loss and multipath distortion of signals and its method of processing them. In evaluating the improvements achievable with space diversity, the accepted practice has been to use the single frequency fading improvement factor formulation in Recommendation ITU-R P.530, or similar formulations verified for regional application, particularly for thermal noise considerations in calculating outage probabilities (see § 4).

By reducing the effective incidence of deep fading, space diversity can reduce the effects of various types of interference. In particular, it can reduce the short-term interference effects from cross-polar channels on the same or adjacent channel frequencies, the interference from other systems, and from within the same system.

Linear amplitude dispersion (LAD) is an important component of waveform distortion and quadrature cross-talk effects, and can be reduced by the use of space diversity. Diversity combining designed specifically to minimize LAD (see Recommendation ITU-R F.752) is among the methods that are particularly effective in combating this distortion.

The improvement derived from space diversity will depend upon how the two signals are processed at the receiver. Two examples of techniques are “hitless” switching and variable phase combining (see Recommendation ITU-R F.752). The “hitless” switch selects the receiver which has the greater eye opening or the lower error ratio and the combiners utilize either co-phase or various types of dispersion-minimizing control algorithms. “Hitless” switching and co-phase combining provide very similar improvement factors.

3.1.2 Frequency diversity

The frequency diversity improvement in a digital radio hop with a 1 + 1 configuration depends on the correlation of degradations (for example, fade depth, amplitude and group-delay dispersion) in the two radio-frequency (RF) channels. Experimental results show a low correlation of amplitude dispersion between two 30 MHz wide channels separated by 60 MHz. The largest frequency diversity improvement can be achieved usually using cross-band frequency diversity.

In $N + 1$ systems the frequency diversity improvement applicable to a working channel decreases as the number of working channels increases. In considering the use of frequency diversity with a multi-hop switching section, it must be taken into account that the frequency diversity improvement depends both on the correlation of the degradation between RF channels within one hop and at the same time on the other hops of the same switching section.

In order to achieve the predicted frequency diversity improvement in digital radio systems, the switching system must operate in a "hitless" mode. Furthermore, the overall switching procedure has to be completed before significant degradation of the traffic channel occurs. A response time of about 10 ms or less is suitable for this purpose.

3.2 Adaptive channel equalization

Some form of receiver equalization is usually necessary in the radio channel. The equalizer must be adaptively controlled to follow variations in transmission characteristics as propagation conditions vary. The equalization techniques employed can be classified into two groups, depending on whether their mode of operation is more naturally described in the frequency or time domain: "frequency domain equalization" and "time domain equalization".

3.2.1 Frequency domain equalization

This type of equalizer comprises one or more linear networks that are designed to produce amplitude and group delay responses, to compensate for the transmission impairments considered most likely to cause a degradation of system performance during periods of multipath fading.

3.2.2 Time domain equalization

For digital systems, time-domain signal processing can be considered as the most natural equalization technique, since it attempts to combat intersymbol interference directly. Control information is derived by correlating the interference that appears at the decision instant with the various adjacent symbols producing it, and is used to adjust tapped delay line networks to provide appropriate cancellation signals. This type of equalizer has the ability to handle simultaneously and independently the distortions which arise from amplitude and group delay deviations in the faded channel, thereby providing compensation for either minimum-phase or non-minimum phase characteristics.

In systems employing quadrature modulation, important destructive effects of fading are known to be associated with cross-talk generated by channel asymmetries. Consequently, to be of value, a time-domain equalizer must be capable of providing the means for quadrature distortion compensation.

3.2.3 Performance improvement factors

Digital radio system outages are caused by a combination of three main degradations: interference, thermal noise and waveform distortion. Equalization is generally only effective against the last of these. Consequently, in considering the performance improvements associated with the use of adaptive equalizers, it is clear that the largest reductions in outage time will occur on hops where signal distortion is known to be the prime cause of system failure.

3.3 Adaptive equalization in combination with space-diversity combining

Dramatic reductions in the incidence of multipath outage can be achieved when adaptive channel equalization is combined with space diversity. Measured total outage time improvement usually exceeds the product of the corresponding individual improvements obtained from diversity and equalization separately, showing that an important synergistic interaction is taking place.

The improvement for space diversity together with equalization is approximately equal to the product of the space-diversity improvement and the square of the equalizer improvement. This seems most accurate for the switched diversity case.

3.4 System design considerations in the presence of propagation ducts

Ducts are known to exist in certain geographical areas at elevations up to and exceeding 1 000 m. In locations where ducts are known to exist, and digital microwave radio-relay systems are to be operated, attention should be given to the following factors in system design:

– the antenna pointing and position,
– the antenna beamwidth, required to minimize the amount of energy radiated towards or received from reflection layers and from the ground,
– the modulation scheme used, in order to increase the symbol duration,
– the path geometry, required to minimize the probability of destructive reflections.

4 Calculation of outage probabilities

In digital systems, outage times are caused by waveform distortion due to frequency selective fading, interference and thermal noise. The total outage time will be dependent on these three contributors. There are various methods for calculating the outage time of digital systems which will be discussed briefly in this section. Typical input parameters for these methods include:

– path length,
– operating frequency,
– antenna radiation pattern,
– diversity parameters,
– surface roughness,
– path clearance,
– climatic zone.

The conventional method for calculating outage times for analogue systems is based on the concept of single-frequency fades and is therefore not directly applicable to high-capacity digital radio-relay systems. An increase in the fade margin, which in analogue systems will tend to reduce the effect of thermal noise, will not improve the performance of digital systems if multipath fading has already collapsed the eye-diagram amplitude to zero. It follows that increasing the transmitter power cannot be employed as the only means of making digital radio systems meet their outage requirements.

Three general approaches have been used in the development of outage prediction methods: fade margin methods, signature curve methods, and methods using the LAD**.** As yet, there are insufficient data to conclude that one of these approaches is clearly superior than the others. Nevertheless, a set of methods for unprotected and protected systems (space, frequency, and angle diversity), including dual polarization co-channel systems, are given in step-by-step form in Recommendation ITU-R P.530. The performance reduction due to distortion is estimated using a signature approach. The methods of Recommendation ITU-R P.530 are recommended, unless other methods are available for a region that are known to be more accurate.

In order to clarify the general approaches, and the many variations that are available in various countries and regions of the world, they are described in the following subsections.

4.1 Fade margin methods

The use of fade margins as system characteristics derives from the well-known fading law for multipath fading at a single frequency. The time, T, in a heavy fading month that the received voltage level is equal to or less than L, relative to the free-space value of unity, is given by $T = AL^2$, where A is a proportionality constant determined by the number of seconds in a month and the path characteristics.

The performance of digital radio systems is not solely determined by the thermal fade margin: the concept of “net” or “effective” fade margin for digital systems must be used. By substituting net fade margin for thermal fade margin the outage time on the hop can be approximately obtained from Recommendation ITU-R P.530. The “net” fade margin is defined as the single frequency fade depth (dB) that is exceeded for the same number of seconds as a chosen BER threshold of, for example, 1×10^{-3}.

4.2 Signature curve methods

Signatures can be used to compute outages, and compare the relative sensitivity of different digital radio systems to the effects of frequency selective fading.

4.2.1 Measurement of signatures

Signatures can be measured by approximating actual fades by a two-ray simulator. The simplified three-ray model has the transfer function:

$$\mathrm{H}(\omega) = a\left[1 - b \exp\left(-j\,(\omega - \omega_0\right)\tau\right] \tag{1}$$

where a unity amplitude direct ray, and a ray of amplitude, b, delayed by τ is assumed, and a is a scaling factor. The “notch” point of this fade is f_0 away from the channel centre frequency, and has a depth $B = -20 \log \lambda$ with $\lambda = 1 - b$. The signature is then the plot of critical value B_c, as a function of f_0 at the outage error ratio. Although a value of 6.3 ns for τ has been used by several administrations, and the associated statistical distributions for b and f_0 have been determined from the study of a large number of fading events, signatures are sometimes measured for other values of τ. Non-minimum phase fades can be taken into account by equation (1) by means of negative values of the delay τ.

Some outage calculation methods assume τ to be a continuous random variable. Therefore, in these cases scaling rules are needed to estimate the variation of $b_c(\tau)$ with τ. Different scaling rules for $b_c(\tau)$ have been proposed. The linear one, applicable for small delays only, indicates that the height in wavelengths (λ) is proportional to τ. More precise scaling rules may also be applied.

Signature width $W(f_0)$ remains practically constant vs. delay, except for the case when delay approaches to zero, when it doubles for halving delay.

4.2.2 Normalized system parameter (K_n)

The effect of equipment characteristics is expressed through the values of normalized system parameter K_n, where this parameter is evaluated from measured system signatures. Conceptually, one can consider the normalized system parameter as being evaluated from a "normalized system signature". If one scales system signatures to a specified baud period (1 ns) and relative echo delay (1 ns), then such scaled system signatures, known as "normalized signatures", are a characteristic of the system parameters such as modulation method, roll-off factor and type of equalizer. Using a rectangular approximation for the signature, K_n is given by:

$$K_n = (T^2 \cdot W \cdot \lambda_a) / \tau_r \tag{2}$$

where:

- T: system baud period (ns)
- W: signature width (GHz)
- λ_a: average of (linear) signature $\lambda_c(f) = 1 - b_c(f)$
- τ_r: reference delay for λ_a (ns).

Table 1 shows values of K_n for receivers without adaptive equalization. The use of adaptive baseband transversal equalizers improves system performance so the figures for the normalized signature area K_n are normally reduced to about 1/10 of the values reported in Table 1.

TABLE 1

Values for K_n for various modulation methods where no equalizer is employed

Modulation method	K_n
64-QAM	15.4
16-QAM	5.5
8-PSK	7.0
4-PSK	1.0