RECOMMENDATION ITU-R F.1093-1*

EFFECTS OF MULTIPATH PROPAGATION ON THE DESIGN AND OPERATION OF LINE-OF-SIGHT DIGITAL RADIO-RELAY SYSTEMS

(Question ITU-R 122/9)

(1994-1997)

The ITU 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 radio systems;

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

c) that methods of predicting the effects of multipath fading on the error performance of a radio system are needed for link planning or for comparing alternative designs,

recommends

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

2 that the prediction methods described in Annex 1 may be used for guidance in radio link planning;

3 that the choice of diversity reception and adaptive equalization for a digital radio-relay system should include the considerations of Annex 1; also Recommendation ITU-R F.752 "Diversity techniques for radio-relay systems" should be taken into account.

ANNEX 1

Effects of multipath propagation on design and operation of line-of-sight digital radio-relay systems

1 Introduction

The purpose of the present Annex is to furnish guidance on 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.

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

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 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 Recommendation ITU-R F.752.

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. Various structures have been proposed, following the alternative models of the multipath channel presented in § 4 (see Table 1).

TABLE 1

Generic type	Description of equalizer		Complexity of implementation	Fade characteristic and position of maximum attenuation			
				Minimum phase		Non-minimum phase	
				Out-of-band	In-band	Out-of-band	In-band
Frequency-domain equalizers	F1	Amplitude tilts	Simple	2	1	2	1
	F2	F1 + parabolic amplitude	Simple	2	2	2	2
	F3	F2 + group delay tilt	Complex (moderately complex)	3	2	3(1)	2(1)
	F4	F3 + parabolic group delay (For F3 and F4 ratings in brackets apply “minimum phase” control assumptions)	Complex (moderately complex)	3	3	3(1)	3(0)
	F5	Single tuned circuit (“agile notch”)	Simple	3	3	1	0
Time domain equalizers	T1	Two-dimensional linear transversal equalizer	Moderately complex/complex	3	2	3	2
	T2	Cross-coupled decision feedback equalizer	Moderately complex	3	3	2	1
	T3	T1 + T2 full time domain equalization	Complex	3	3	3	2

Effectiveness of equalization

3: produces a well equalized response

2: produces a moderately equalized response

1: produces a partially equalized response

0: not effective.

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 (see Table 1).

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.

Table 1 summarizes the performance of different classes of adaptive equalizer considered in this section. Implementation complexity is considered as well as effectiveness of equalization, and the assessments are made for both minimum-phase and non-minimum phase fading characteristics.

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.

Another input to some of the prediction methods is a multipath propagation model. Models that have been used include:

a) Ray models:

- multiple-echo model;
- general three-ray model;
- phase-shifted two-ray model with flat attenuation (also referred to as a “simplified three-ray model”);
- joint characterization of a space diversity channel pair with simplified three-ray model;
- improved two-ray model with random delay, flat attenuation and random echo amplitude;
- normalized two-ray models.

b) Polynomial models in the frequency domain:

- complex polynomials;
- real polynomials of amplitude and group delay.

c) Parametric models:

- two point method with fixed frequency spacing.

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}.

The composite fade margin approach accounts for the dispersiveness of the fading on a hop by using dispersion ratios, which can be used as a parameter to compare the dispersiveness of different hops in relation to single frequency fading. The net fade margin is regarded as the composite of the effects of thermal noise, intersymbol interference due to multipath dispersion, and interference due to other radio systems. At the detector of a radio receiver during fading these three sources will give three voltage components, which will add on a power basis since they are independent. Thus the total outage time becomes the sum of the contributions due to single-frequency fading, dispersion and interference.

The dispersive fade margin (DFM) may be determined from the measured net fade margin by correcting the latter for any thermal noise or interference contributions, if necessary. Since the DFM reflects the impact of multipath dispersion on the radio system, its value must depend on the fading and on the radio equipment. The first step is to determine the DFM of a radio system on a path with known dispersion ratio of DR_0. This value, (dB), is taken as a reference dispersive fade margin (DFMR). Then the DFM that would be measured or predicted on a path with a dispersion ratio of DR is given by:

$$DFM = DFMR - 10 \log (DR/DR_0) \tag{1}$$

Calculations based on this procedure have shown good agreement with measured radio performance in the field in the presence of interference, as well as with detailed estimates based on propagation models.

DR is given by the following relationship:

$$DR = \frac{T_{IBPD}}{T_{SFF} \cdot BF^2} \tag{2}$$

where:

T_{IBPD} : amount of time that a chosen in-band power difference (IBPD) (i.e. the amount of dispersion on a hop) value is exceeded

T_{SFF} : amount of time that a chosen single frequency fade (SFF) value is exceeded

BF : bandwidth correction factor, which is the ratio of 22 MHz to the measurement bandwidth.

Modern digital radio systems (e.g. 64-QAM) equipped with adaptive time domain equalizers, experience outage time (i.e. BER $> 1 \times 10^{-3}$) due to IBPD distortion in the region of 10 to 15 dB. Thus a suitable threshold for comparing dispersion would be 10 dB. The values of dispersion ratio measured on number of hops in North America and Europe are in the range 0.09 to 8.1 for hop lengths in the range 38 to 112 km. This is based on a value of 10 dB and 30 dB for IBPD and single frequency fade, respectively.

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:

$$\mathrm{H}(\omega) = a\left[1 - b \exp\left(-j\,(\omega - \omega_0)\,\tau\right)\right] \tag{3}$$

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 (3) 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 Outage computations using signatures

The probability of outage caused by multipath fading, P, can be computed from the outage probability due to selective fading, P_s, and the outage probability due to thermal noise, P_f, using the following formula:

$$P = \left(P_s^{\alpha/2} + P_f^{\alpha/2}\right)^{2/\alpha} \tag{4}$$

where $\alpha = 1.5 \ldots 2$

P_f is equal to the probability that the system flat fade margin is exceeded and can be calculated according to Recommendation ITU-R P.530. The effect of interfering signals may be considered equivalent to a margin reduction.

Several methods have been published that use the concept of signatures to compute P_s. In this section four of these methods are discussed, being referred to as Method A, Method B, Method C and Method D. (The method recommended in Recommendation ITU-R P.530 is based on Method B.) In these methods P_s is given by the product of the probability of multipath fading, η, and the probability of outage by intersymbol interference during multipath fading, $P_{s/mp}$:

$$P_s = \eta \cdot P_{s/mp} \tag{5}$$

To calculate $P_{s/mp}$, a single echo fade model is assumed with the relative echo amplitude, b, the echo delay, τ, and the notch frequency offset, f_0, as random parameters. The effect of equipment characteristics on the outage probability is expressed by the system signatures.

The differences between the outage prediction Methods A, B, C and D concern the value of α in equation (4), the value of η in equation (5), the probability density functions (pdf's) for b, τ and f_0 and the implementation of system signatures into the method. In some of the methods the pdf's for b and τ are chosen such that the relative occurrences of minimum phase and non-minimum phase fades are taken into account.

– α: the factor α determines, according to equation (4), whether total outage probability is equal to the simple sum $P_s + P_f$ (that is $\alpha = 2$) or that a more conservative value results ($\alpha = 1.5$). Methods B and D assume $\alpha = 2$, whereas in Method C $\alpha = 1.5$.

– η: the propagation parameter η in equation (5) can be theoretically related to the deep fade occurrence factor, P_0 (Recommendation ITU-R P.530). In Method C, η is related to the mean value and standard deviation of the concurrent slow fadings. A simplified empirical rule is applied in Method B and also adopted in Method D:

$$\eta = 1 - \exp\left[-0.2 \cdot P_0^{3/4}\right] \tag{6}$$

– $p_b(b)$: different assumptions have been proposed for the pdf of the relative echo amplitude B: uniform (Method A), exponential (Method B), Weibull (Method C) and Rayleigh-over-Rayleigh (Method D).

– $p_\tau(\tau)$: two different echo delay distributions are assumed. In the first case the echo delay τ has a negative exponential distribution with mean value τ_m that depends on path length D. The following empirical relation between τ_m (ns) and D (km) is used for paths without significant surface reflections:

$$\tau_m = \tau_{m0} \cdot (D / 50)^n \tag{7}$$

where n falls in the range 1.3 and 1.5 and τ_{m0} is the mean relative delay for a standard path of 50 km. The value of τ_m characterizes the severity of fading.

Methods A, B and C, which assume exponentially distributed delays, lead to τ_{m0} = 1.0 ns (Method A), 0.7 ns (Method B) and 0.5 ns (Method C). In the second case, a Gaussian distribution with mean μ and variance ν^2 is assumed. These parameters can be chosen independently, permitting a more accurate fit to measured (or calculated) density functions for individual hops than the sole parameter of the exponential density allows. In the absence of any hop-specific information, the model assumes:

$$\begin{aligned} \mu &= 0.70 \cdot (D / 50) \quad \text{ns} \\ \nu^2 &= 0.49 \cdot (D / 50) \quad \text{ns}^2 \end{aligned} \tag{8}$$

The Gaussian distribution includes both positive and negative delays.

– $p_{f_0}(f_0)$: f_0 is uniformly distributed in all the four methods.

– MPF/NMPF: account must be taken of the relative occurrences of minimum phase fade and non-minimum phase fade conditions by computing outage probability separately when signatures for minimum phase and non-minimum phase are different. Methods C and D allow the relative occurrence probabilities of minimum and non-minimum phase fades to be identified: for deep fades the probabilities tend to be equal, while for shallow fades the minimum phase case predominates.

– Signatures: the four methods use signatures to express the effect of equipment characteristics (such as modulation scheme, roll-off factor and equalization) on the outage probability, but the way in which signatures are applied is different for each method.

In Method D the influence of equipment characteristics is directly expressed by the area of the measured (or calculated) signature at an arbitrary reference delay divided by that delay. Minimum and non-minimum phase conditions are taken into account in evaluating the signature area. In Methods A and B 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:

$$K_n = (T^2 \cdot W \cdot \lambda_a) / \tau_r \qquad (9)$$

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 2 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 2.

TABLE 2

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

Table 3 summarizes the main properties of the four methods.

TABLE 3

Four methods to compute outage probability *P* using signatures

	A	B	C	D
$p_b(b)$	Uniform	Exponential	Weibull	Rayleigh-over-Rayleigh
$p_\tau(\tau)$	Exponential	Exponential	Exponential	Gaussian
$p_{f_0}(f_0)$	Uniform	Uniform	Uniform	Uniform
Minimum phase fade/non-minimum phase fade	No	No	Yes	Yes
Signatures	K_n	K_n	K_n, or as measured	Area divided by τ_r
η	–	$1 - \exp\left(-0.2\ P_0^{3/4}\right)$	From μ and σ of concurrent slow fadings	As in Method B
α	–	2	1.5	2

When use is made of normalized signatures, all the methods lead to the same conclusions, which may be summarized according to the following relationship:

$$P_{s/mp} = C \cdot p_b(1) \cdot K_n \cdot <\tau^2> / T^2 \tag{10}$$

where T and K_n are as above, and

$<\tau^2>$: second moment of $p_\tau(\tau)$ (ns^2). For exponentially distributed delays, $<\tau^2>$ is equal to $2 \cdot \tau_m^2$, and for Gaussian distributed delays $<\tau^2> = \mu^2 + \nu^2$

$p_b(1)$: value of $p_b(b)$ for $b = 1$

C: constant factor.

Methods A, B and C yield the same results if $C \cdot p_b(1)$ is set to 1.0 for Method A, 2.16 for Method B and to 4.0 for Method C. In Method D, K_n is not used to compute $P_{s/mp}$, but this method leads to an approximation for $P_{s/mp}$ similar to formula (10):

$$P_{s/mp} = p_b(1) \cdot <\tau^2> \cdot W \cdot (b_{cN} - b_{cM}) / \tau_r \tag{11}$$

where:

$b_{cN}/_M$: average critical echo amplitudes for non-minimum/minimum phase conditions at reference delay τ_r.

To assess the validity and range of applicability of the methods, it is beneficial to compare the computed total outage time. An efficient comparison was made in Europe on the basis of hypothetical links which were defined by a set of hop and system parameters. This comparison showed that although the methods used diverge in their approach to outage computation, the predictions generally agree within one order of magnitude for an unprotected channel, as long as the same single fade depth statistics are assumed. The observed and the predicted outage times agree within a factor of two when the measured fade depth distribution of a real hop is applied to one of the methods.

4.2.3 Outage computation in the presence of diversity

The outage prediction methods of § 4.2.2 have been extended to systems using some type of diversity countermeasures (space diversity, in-band and cross-band frequency diversity), and employing either baseband bit combining ("hitless"-switching) or in-phase combining. Results may be summarized with the following relationship:

$$P_{sdiv/MP} = (P_{s/MP})^2 / \Delta_{sel} \tag{12}$$

where Δ_{sel} is a factor which accounts for the correlation between the diversity channels. This law has been experimentally verified.

When frequency-selective effects dominate, P_{sdiv} as given above approximates to the actual outage probability P_{div} of the system; however, when thermal noise dominates:

$$P_{div} = P_{fdiv} \tag{13}$$

$$P_{fdiv} = P_f^2 / \Delta_{flat} \tag{14}$$

where:

P_f : outage probability due to thermal noise

Δ_{flat} : factor that accounts for the correlation between the diversity channels.

4.3 Outage computation using linear amplitude dispersion (LAD) statistics

Propagation distortion consists of amplitude and delay distortion. Distortion caused by two-path fading has a complex shape and cannot be composed completely by LAD and quadratic distortion. However, linear amplitude dispersion is dominant. The effects of other distortions, such as delay distortion or LAD distortion, on outages, are described accurately and appropriately by the threshold LAD. This means that outage probability caused by frequency selective fading can be estimated if equivalent LAD is given and LAD occurrence is known. Detailed studies have been conducted on LAD occurrence probability, and a method to calculate the occurrence probability has been established, taking into account path profile features.

In the case of Rayleigh fading the probability of outage when LAD exceeds a threshold Z is given by:

$$P_d = 2\alpha, \text{ for single reception} \tag{15}$$

$$\alpha = 0.5\left(1 - \frac{1 - Z^2}{\sqrt{(1 + Z^2)^2 - 4r Z^2}}\right) \tag{16}$$

where r is the frequency correlation coefficient.

The same method can be extended to compute outage when maximum power space diversity combiner is employed. It can be shown that:

$$P_{ds} = 6\alpha^2 - 4\alpha^3 \qquad \text{(space diversity)} \tag{17}$$

To estimate complete system outage, the probability of outages caused by intersymbol interference, thermal noise and the synergistic effects must be clarified. As the system thermal fading margin is easily determined, outage probability due to thermal noise and interference can be calculated using the methods for predicting the fading distribution due to multipath and related mechanisms as given in Recommendation ITU-R P.530.

An outage probability calculation method is given as follows:

– Using average b and τ values based on a particular path profile, a frequency correlation coefficient between any two different frequencies is calculated.

– When a transmitted waveform characterized by roll-off factor, symbol rate, or modulation scheme is given, the LAD causing outages (Z) is determined by calculation or experiment. The outage probability, P_d, caused by waveform distortion can be obtained by equation (15) or (17).

– The outage probability, P_n, caused by interference and thermal noise can be estimated by calculating the occurrence probability of the thermal fade margin F_s of the system during Rayleigh fading.

– Overall outage probability P_0 is given as:

$$P_0 = P_r (1 + \eta)(P_d + P_n) \tag{18}$$

where:

P_r: occurrence probability of Rayleigh fading, and

η: synergistic effect.

This formula can be simplified as follows:

$$P_0 = P_r \cdot \xi \cdot max(P_d, P_n) \approx \begin{cases} P_d + P_n & \text{(single reception)} \\ \left(\sqrt{P_{ds}} + \sqrt{P_n}\right)^2 & \text{(space diversity)} \end{cases} \tag{19}$$

where ξ is a correction coefficient and $max(P_d, P_n)$ means the larger of P_d and P_n. The net fade margin for the system is given by the fade value, which gives probability, P_0, during Rayleigh fading. This estimation method can also be applied to space diversity reception.