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ETSI Secretariat

Postal address
F-06921 Sophia Antipolis Cedex - FRANCE

Office address
650 Route des Lucioles - Sophia Antipolis
Valbonne - FRANCE
Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16
Siret N° 348 623 562 00017 - NAF 742 C
Association à but non lucratif enregistrée à la
Sous-Préfecture de Grasse (06) N° 7803/88

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c= fr; a=atlas; p=etsi; s=secretariat

Internet
secretariat@etsi.fr
http://www.etsi.fr

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Intellectual Property Rights

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Transmission and Multiplexing (TM).

1 Scope

The present document deals with performance prediction models for Digital Radio Relay Systems (DRRS). These models are used in two areas of application:

1) **equipment and system design:**

   performance prediction models are used in the system development stage, in that they allow for a comparison of proposed system concepts in terms of expected performance;

2) **individual link planning:**

   performance prediction models support the choice of system dimensioning (e.g. antenna diameter) and system configuration (including propagation countermeasures) that is necessary to comply with the desired performance objectives.

Models considered in the present document have been developed independently in Germany (with two versions for diversity improvement calculation), France, Italy and the United Kingdom. Descriptions of each model are given in the annexes A to D, with additional references where appropriate.

NOTE: Not included in this document is an additional model produced by British Telecom, which was published in ETSI/STC-TM4(90) 109, Digital Radio Relay Systems, Volume 2, Executive Summary of meeting No.4, Held in Montreux 5-9 November 1990.

The objectives of the present document are as follows:

- to define an outline specification for the prediction models;
- to examine all models proposed for compliance with the specification;
- to test the models against measured results, to establish their accuracy and to identify areas where a need exists for improvement;
- to compare and verify the models.

2 References

References may be made to:

a) specific versions of publications (identified by date of publication, edition number, version number, etc.), in which case, subsequent revisions to the referenced document do not apply; or

b) all versions up to and including the identified version (identified by "up to and including" before the version identity); or

c) all versions subsequent to and including the identified version (identified by "onwards" following the version identity); or

d) publications without mention of a specific version, in which case the latest version applies.

A non-specific reference to an ETS shall also be taken to refer to later versions published as an EN with the same number.

[1] ITU-T Recommendation G.821: "Error performance of an international digital connection forming part of an integrated services digital network".

[2] ITU-T Recommendation G.826: "Error performance parameters and objectives for international, constant bit rate digital paths at or above the primary rate".

[3] ITU-R Recommendation P.530-6: "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems".

[4] ITU-R Report 338-6: "Propagation data and prediction methods required for the line-of-sight radio-relay systems".

Additionally, each annex contains its own set of references.

3 Input and output parameters

In order to compare the proposed prediction models, sets of hypothetical hops are defined as discussed in more detail in clause 5. Unprotected hops, i.e. those without diversity, and protected hops which include frequency, space or angle diversity form the basis for the evaluation exercise. The hypothetical hops are based on a list of input parameters given in table 1. For each set, one input parameter is varied, whereas all others are kept at the nominal value. The nominal value corresponds to a real hop in the United Kingdom. The list of input parameters is the accepted common basis to compute predictions.

The outage parameter for the prediction, being the output parameter, is defined as the outage probability (BER>10^{-3}) in a worst month. As a first approximation, outage due to multipath fading is closely equal to the occurrence of Severely Errored Seconds (SES) defined in ITU-T Recommendation G.821 [1], since the duration of a typical multipath event is generally of the order of a few seconds, whereas a period of unavailability is defined by the ITU-T to start with 10 consecutive SESs.

NOTE: The ITU-T has approved Recommendation G.826 [2] on error performance which may imply a modified value for the BER threshold.

With respect to the precipitation effects, the statistics on precipitation given by the ITU-R are regarded as sufficient. Since precipitation is connected largely with unavailability, the sensitivity analysis comprises only clear air effects. The same eventually applies to the present document as a whole.

4 Real hop predictions

A first approach to compare and evaluate the models considered would be to predict performance on real hops and to compare the results against measured outage.

However, several different assumptions have to be made before undertaking the model predictions, leading to potential divergence in the results. In addition, very few results of measured systems were available to permit a comparison with the predictions. Therefore, the comparison on the basis of hypothetical hops seems to be more relevant for purposes of verification, and the emphasis is placed on this second activity.

5 Hypothetical hop predictions

The models are verified against the outage predictions computed from the parameters of sets of real hop predictions and sets of hypothetical test hops. The following discussion concerns the hypothetical test hops.

A list of 13 test hop parameters, listed in table 1, is identified for specification as input data to the models during the verification process; these represent path, equipment and system parameters of the proposed hypothetical hop. Nominal values based on a real hop, (Charwelton-Copt Oak in the United Kingdom), are agreed for the 13 parameters and each is assigned a realistic "range of variation" over which the models could be exercised and their sensitivities analysed. Model authors then used their models to predict outage time against the variation range specified for each parameter in turn whilst holding all other parameters at their nominal value. Outages are computed at a BER of 10^{-3} for unprotected and protected operation.

The results of the first sensitivity analysis show that the results of the model predictions are spread over about two orders of magnitude for the unprotected system and more for the protected system. The main reason of this behaviour can be identified in the evaluation of the statistics of deep fading which has been used by all the models in order to determine the time percentage of multipath occurrence.

In common with the real hop predictions, a significant reason for the observed divergence in the results is then probably due to the use of different fade depth statistics within the models. Table III ANNEX II of ITU-R Report 338-6 [4] details the exponent values for the frequency and distance parameters forming part of what is generally known as the multipath occurrence factor P_o, where:

$$P_o = KQF^B D^C$$

where D is the path length, F is the frequency, K is a geoclimatic factor, Q is a parameter accounting for the effect of path variables other than F and D.

NOTE: In the meantime, ITU-R has come up with modified formulas for outage prediction, see ITU-R Recommendation P.530-6 [3].

The predictions have been computed with the same KQ factor but the exponents B and C have been regarded as part of each model. Modellers agree that the factors B and C had been chosen to correlate with fading statistics observed within their respective countries and that these values should be fixed for the hypothetical test hop; this would undoubtedly lead to much better convergence between model predictions.

ITU-R Report 338-6 [4] tabulates different values of these parameters according to the climate. In order for the sensitivity analysis to be useful, equal climatic conditions have to be agreed for the hypothetical hop. The contribution to the divergence of predicted outage, due to the use of different values of the parameters B and C, is about one decade. A further step has then been necessary, in which the sensitivity analysis was repeated making use of equal deep fading distributions.

Therefore, to further exercise the models, two sets (set A and set B) of values for B and C have been defined.

Values chosen for these factors are:

Set A: B = 1,0 and C = 3,0 (see figures Set A,1a to Set A,13b);

Set B: B = 0,85 and C = 3,5 (see figures Set B,1a to Set B,13b).

Relations between input parameters and numbers of corresponding figures are given in the last three columns of table 1. The order of figures corresponds with the order of input parameters listed in table 1.

The graphical results depicted in figures Set A,1a to Set B,13b demonstrate that now much better convergence is achieved for both unprotected and diversity protected systems.

It can be seen that the spread on predictions for the unprotected system is generally reduced from about two orders down to below one order of magnitude over the distance ranges normally encountered and that the models behave in a very similar manner for either set of B and C factors. The discontinuities observed in some of the graphs result from the use of discontinuous functions, and in some cases from the numerical granularity of computation or from extrapolation.

Several important conclusions can be drawn from the sensitivity analysis:

5.1 Unprotected systems

A remarkable result is achieved in obtaining such close convergence from the four models by merely fixing the exponents of B and C of the multipath occurrence factor. This result is even more remarkable when one considers:

a) that the models diverge considerably in their approach to the outage computation, e.g. by employing different multipath propagation models and embodying different assumptions for the statistics of echo amplitude and echo delay;

b) that the sensitivity analysis stressed the models beyond the normal parameter combinations met in practice. By varying one parameter with all other parameters fixed, rather extreme conditions are created; these conditions are unlikely to appear in the real world. For example, the parameters hop length and flat fade margin are more likely to be interdependent rather than independent;

c) that models have been derived from measurements taken in the originating country. Differences in the geographical and climatic conditions within some countries could lead to differences in propagation modelling which may not have been reduced by the use of fixed values for exponents B and C.

To complete our discussion of the unprotected results, it is pertinent to state that the amount of convergence obtained by fixing exponents B and C is as large as the remaining spreads between the models. This finding indicates the importance of collecting and processing propagation data to enable better understanding of fading statistics and the development of more precise fading models. However, we should not detract from the excellent agreement obtained between model predictions which leads to the conclusion that considerable confidence can be placed in the unprotected results returned from any one of the models.

5.2 Diversity protected systems

The magnitude of the prediction spreads, although reduced by fixing the exponents B and C, shows less convergence than those obtained from unprotected systems. The reasons for this trend can be summarized as follows:

a) due to the fact that the protected outage is typically proportional to the square of the unprotected outage, the spreads between model predictions expanded;

b) the statistical database available for analysis from experimental work is more limited for diversity operation and statistical uncertainties often arise in the quantitative analysis of the improvement factor. A further complication arises as experimental data is often collected over relatively short periods, whereas many years of data collection and analysis are necessary to assess "worst month" effects;

c) the cost of installation and maintenance of trials with the necessary system configuration, plus reference channels to enable a thorough and precise analysis of results, is usually considered prohibitive. This leads to the deployment of simpler configurations where dependencies are determined by extrapolation of measured results. In this way, uncertainties are often introduced which lead to less accurate modelling.

During the hypothetical test hop analysis, predictions for angle diversity and frequency diversity operation (inband and crossband) were also computed. Figures Set A,7 and Set B,7 each present two predictions for angle diversity reception against the angular separation between the radiation lobes, showing that reasonable convergence is obtained below one degree with some divergence as the separation increases above this value. It must be noted that only first approaches to modelling are presented and as more data is collected, models will be further developed and refined. It is generally agreed that the performance of protected systems is more dependent on a specific path characteristic than an unprotected system: for example, a reflection point on the earth's surface could have a large impact on the attainable improvement from an angle diversity system.

To conclude this discussion on the results of the hypothetical hop analysis, it is important to note that the prediction methods presented by the ITU-R for unprotected and diversity operation are more relevant to narrowband than high capacity digital radio-relay transmission.

6 Model accuracy

The methods used for predicting outage in the models considered follow two basic steps. Firstly, the models estimate fading statistics using hop parameters e.g. frequency, path length, geoclimatic factors etc., and secondly the outage predictions are evaluated using both the estimated fading statistics and radio equipment parameters e.g. signal to noise ratio versus Bit Error Ratio characteristics, system signature etc.

The estimation of fading statistics is based on information provided by the ITU-R and any evaluation of its accuracy is beyond the scope of the present activity.

On the other hand, measured fading data could replace the estimated fading statistics normally evaluated by the models, and outage predictions computed as before. Comparisons between predicted and measured outage determines the accuracy of the part of the models which take into account radio equipment parameters to estimate outage.

As an example, two periods of propagation activity exhibiting a representative mixture of flat and multipath fading have been chosen for this comparison phase.

It was found that in the worst case, there is a discrepancy of less than a factor of about two between measured and predicted results.

7 Conclusions

The work carried out seems to be both unique and important to radio-relay planning. The models tested provide the link between equipment characteristics and network performance. The accuracy of the models is verified as described in the present document. The models are described in detail and are available for use within ETSI.

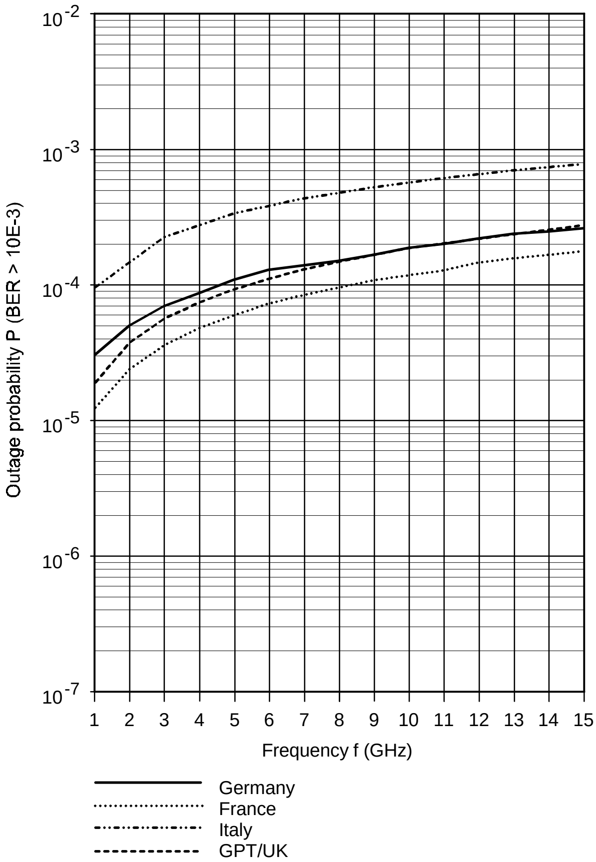
Table 1: List of input parameters and their ranges

Input Parameter	Range	Reference value	Figure numbers		
			Space Diversity		
			without	with	other
Frequency (see note)	1 GHz to 15 GHz	6,2 GHz	A,1a / B,1a	A,1b / B,1b	-
Path length (see note)	10 km to 100 km	50 km	A,2a / B,2a	A,2b / B,2b	-
k ∗ Q factor	1×10^{-8} to 4×10^{-6}	$6,8 \times 10^{-7}$	A,3a / B,3a	A,3b / B,3b	-
Space diversity (see note) (maximum power combination): - antenna gain difference	-	0 dB	-	A,4/B,4	-
- antenna spacing	6 m to 20 m	10 m	-	A,4/B,4	-
Frequency diversity: - inband frequency spacing	30 MHz to 210 MHz	0 MHz	-	-	A,5/ B,5
- cross-band frequency spacing	2 GHz to 6 GHz	0 GHz	-	-	A,6/ B,6
Angle diversity: - angular separation	0,5° to 2°	1,0°	-	-	A,7/ B,7
- main lobe deviation from line-of-sight	-1° to 1°	0°	-	-	A,8/ B,8
Flat fade margin (see note) for BER = 10^{-3}	20 dB to 50 dB	40 dB	A,9a / B,9a	A,9b / B,9b	-
Signature mask (see note) for BER = 10^{-3}, delay 6,3 ns: - width	20 MHz to 40 MHz	29 MHz	A,10a / B,10a	A,10b / B,10b	-
- depth	10 dB to 30 dB	17 dB	A,11a / B,11a	A,11b / B,11b	-
Hop crosspolar discrimination (XPD) (see note)	20 dB to 36 dB	36 dB	A,12a / B,12a	A,12b / B,12b	-
3 dB beamwidth	0,7° to 1,5°	1°	A,13a / B,13a	A,13b / B,13b	-
Adjacent-channel interference rejection	-	27 dB	-	-	-
NOTE: Mandatory input parameters for the certification.					

The list indicates:

- the range of variation of the parameters for the sensitivity analysis (column 2);
- the nominal values of the parameters on the real hop in the United Kingdom (column 3);
- the relation between input parameters and figure numbers (columns 5 to 7);
- letters A and B refer to figure Sets A and B as defined in clause 5.

All relevant definitions, symbols and abbreviations are contained within each individual annex.



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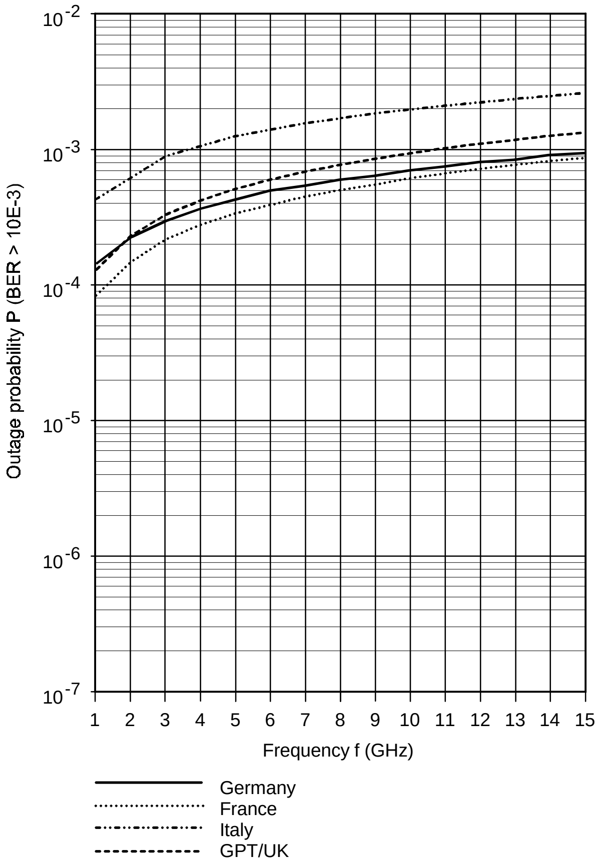

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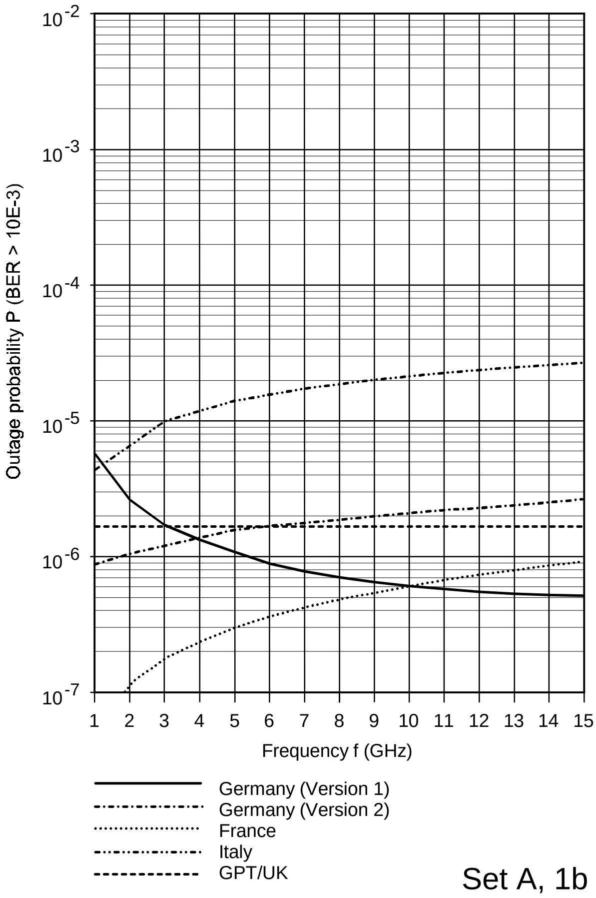

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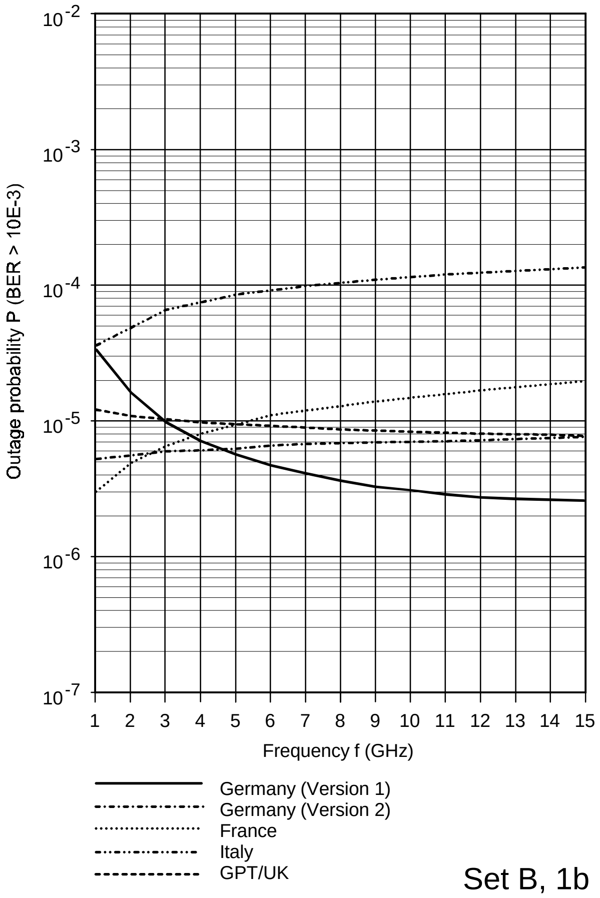

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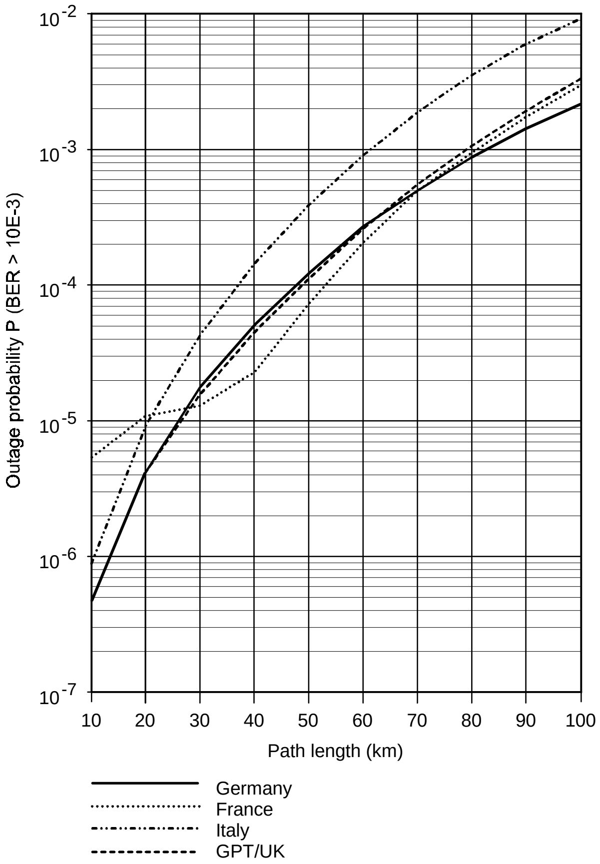

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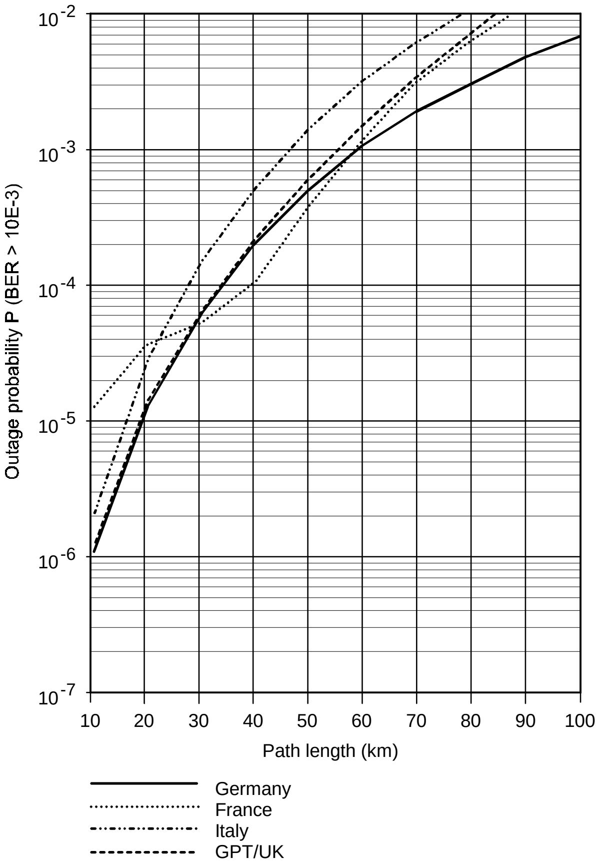

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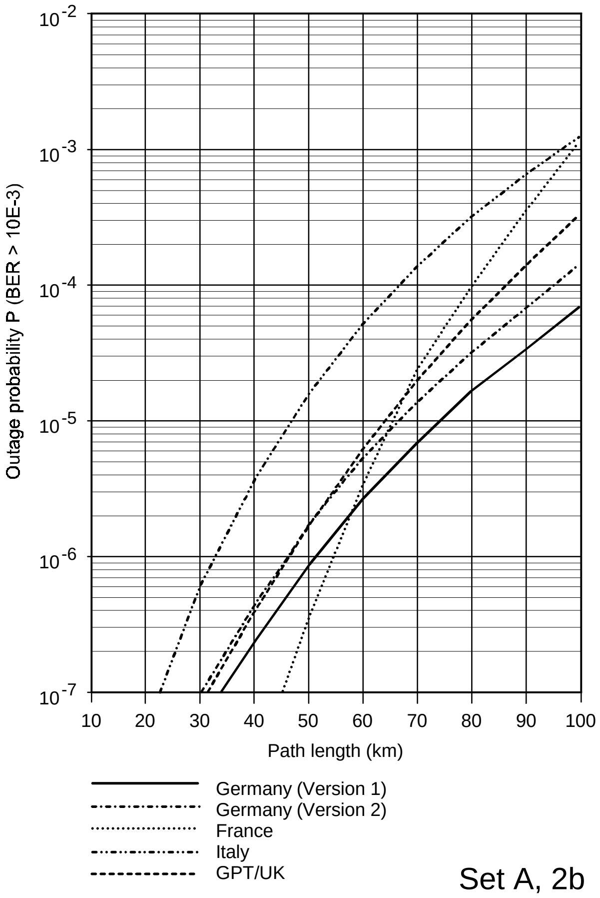

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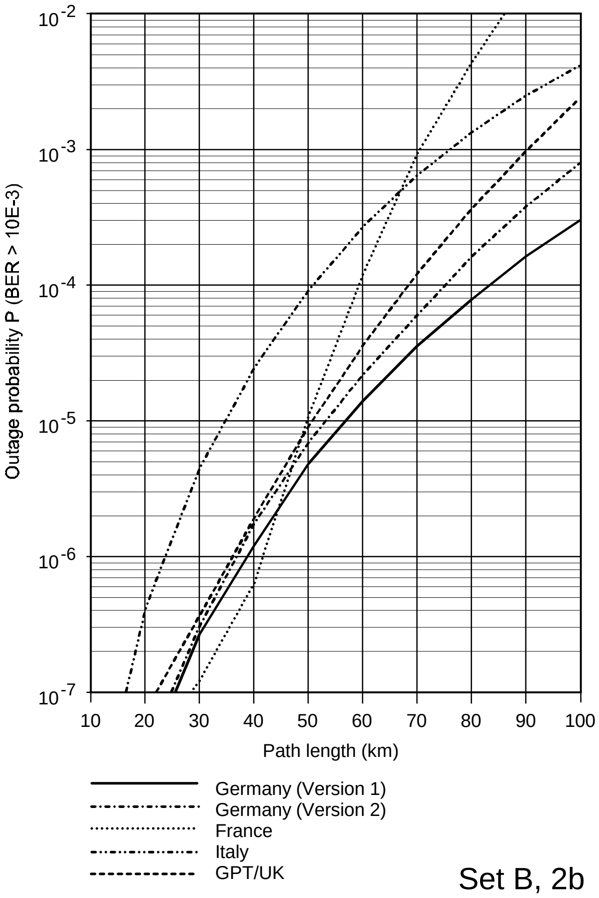

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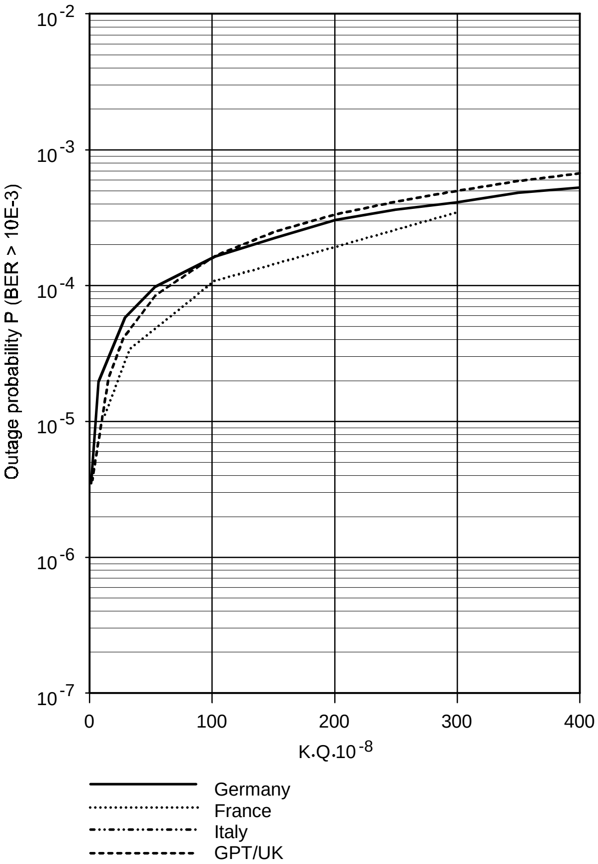

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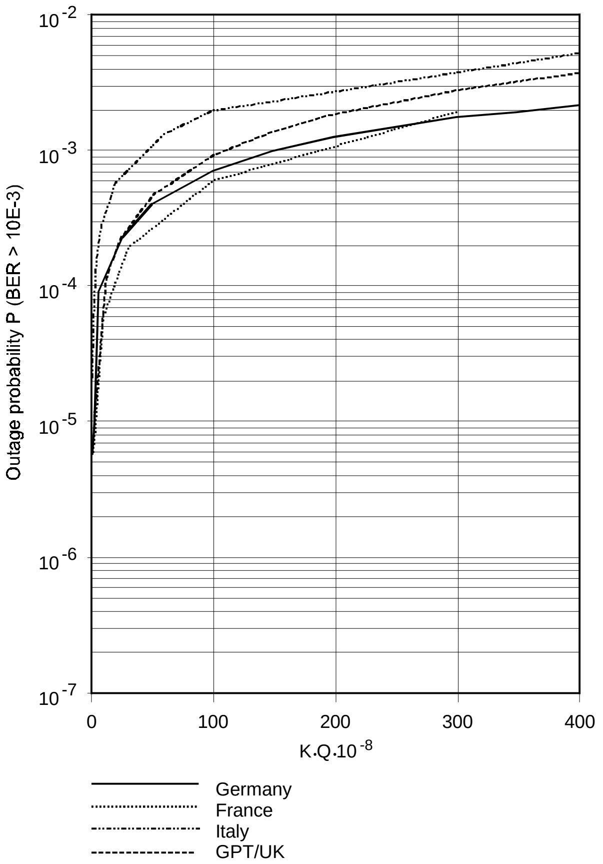

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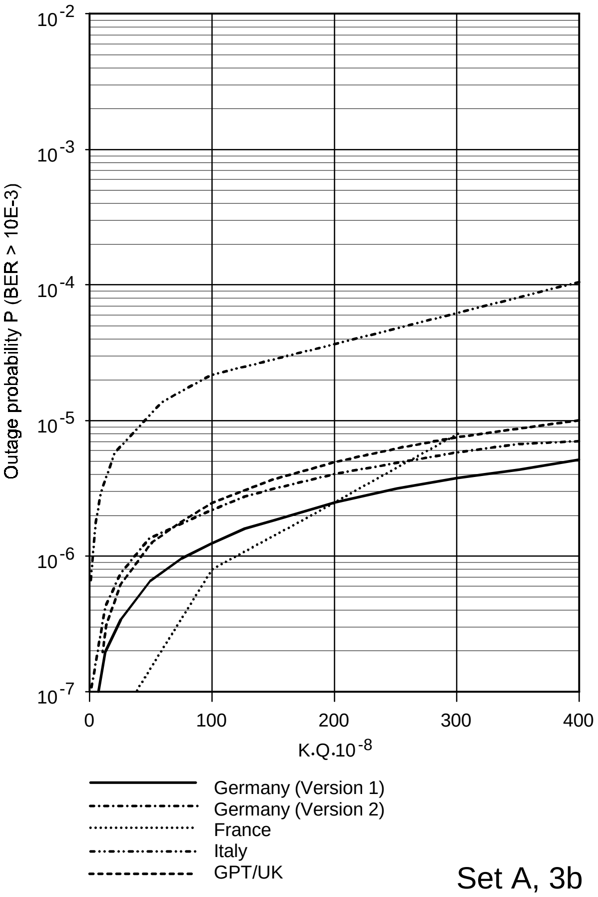

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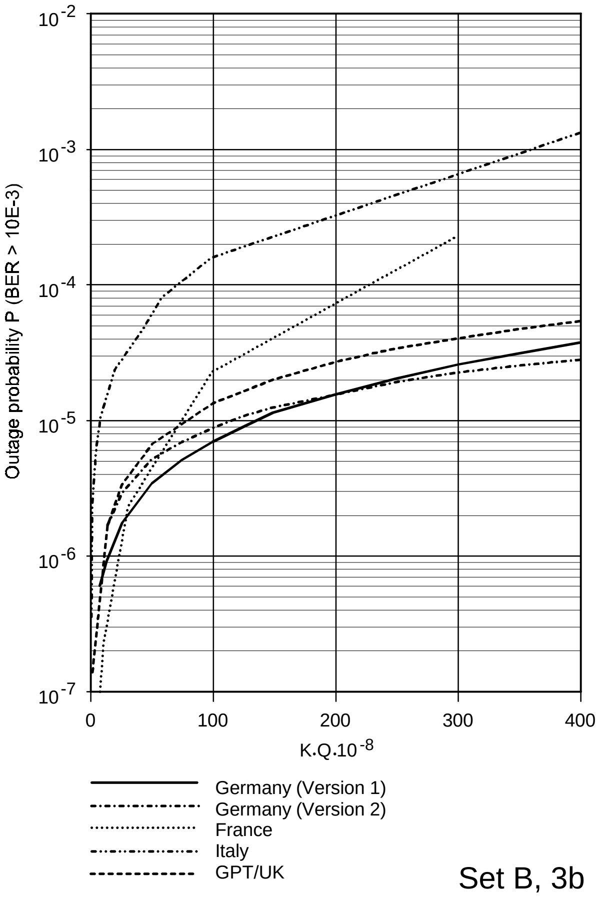

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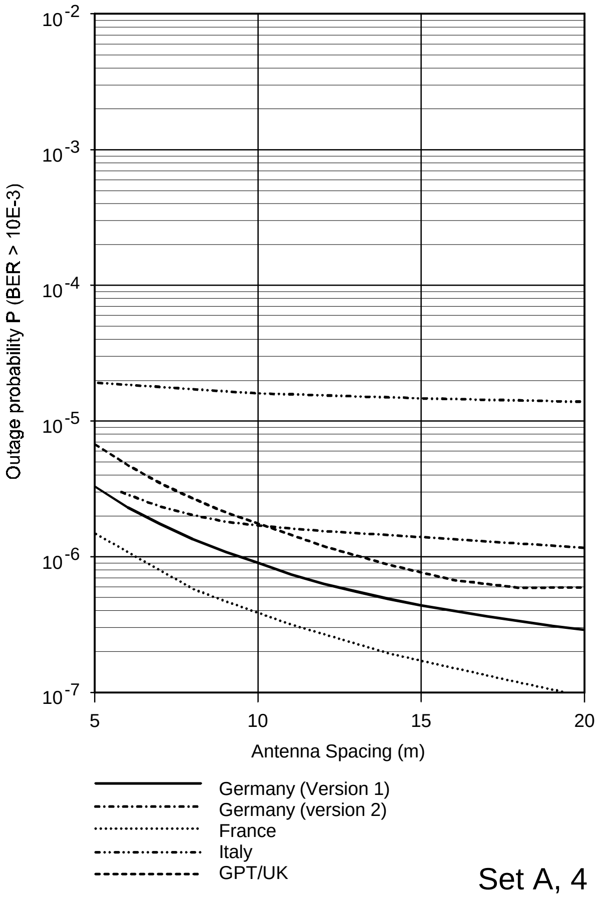

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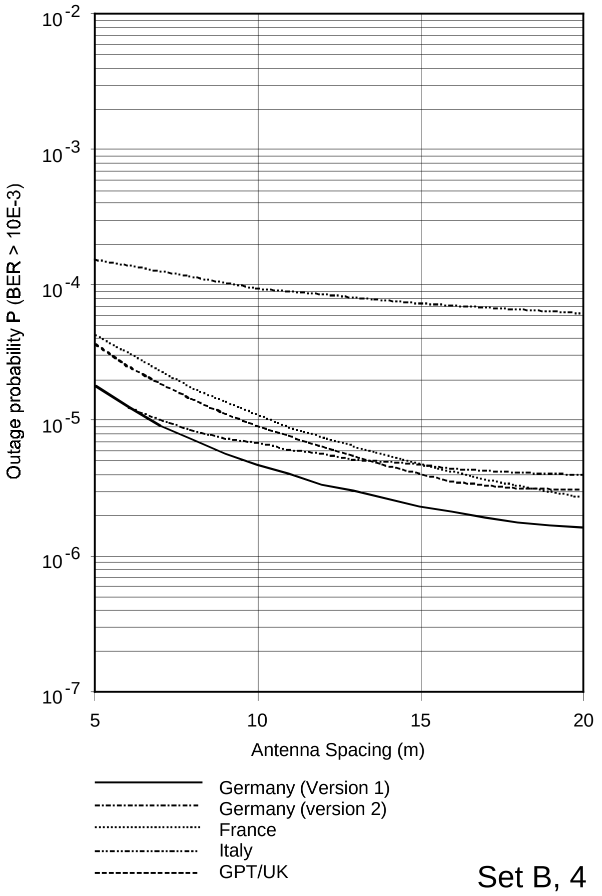

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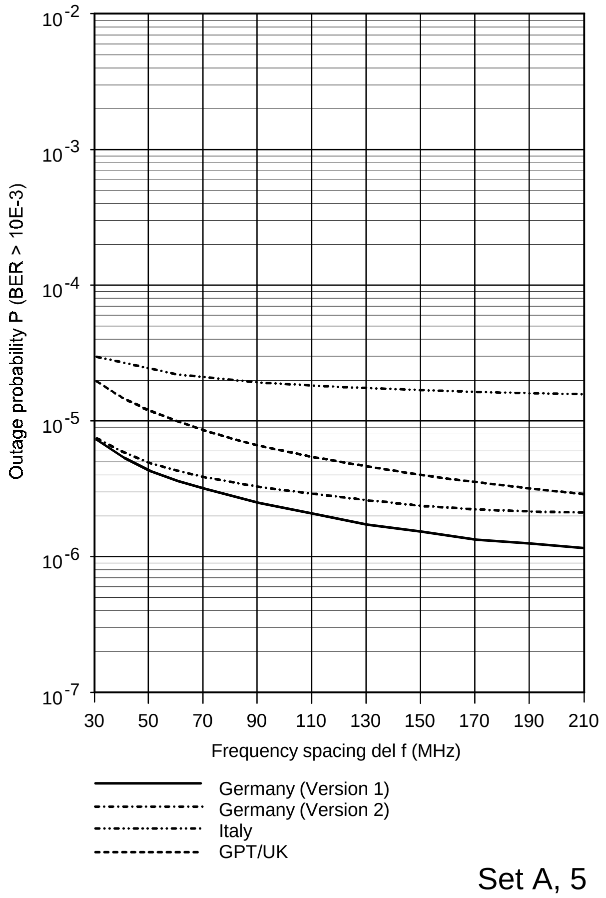

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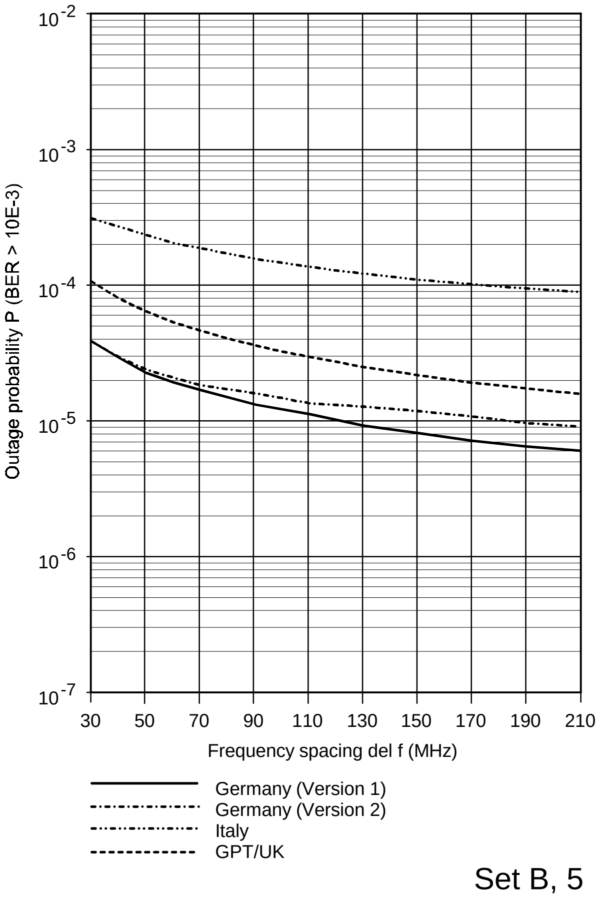

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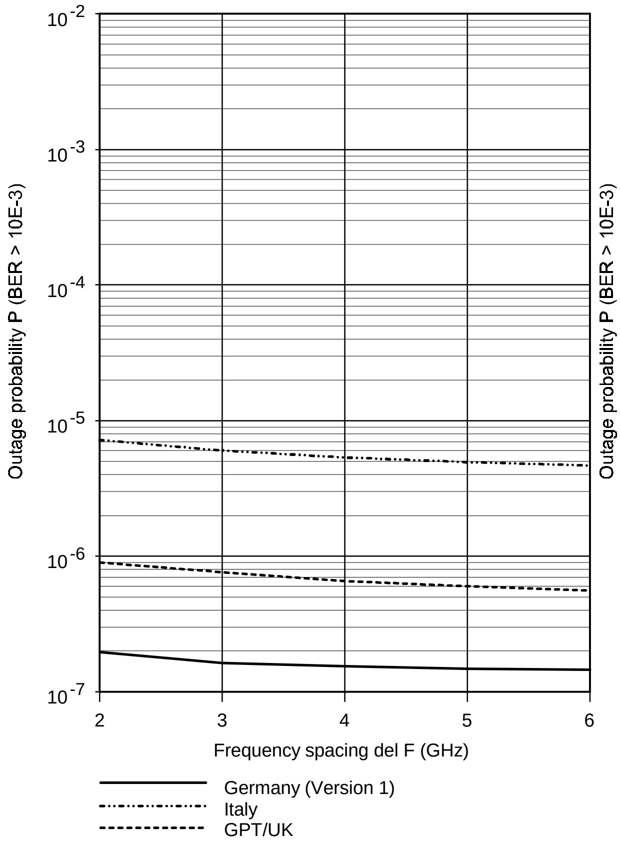

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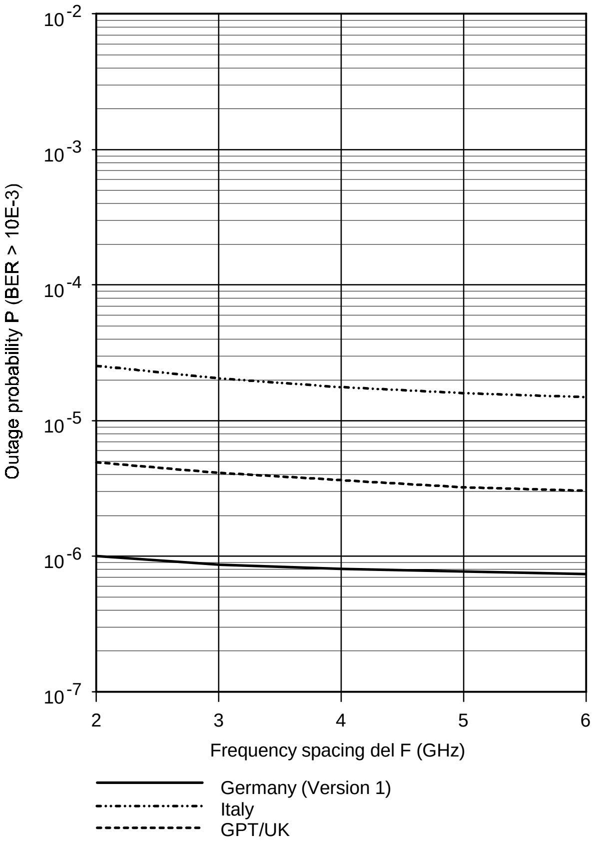

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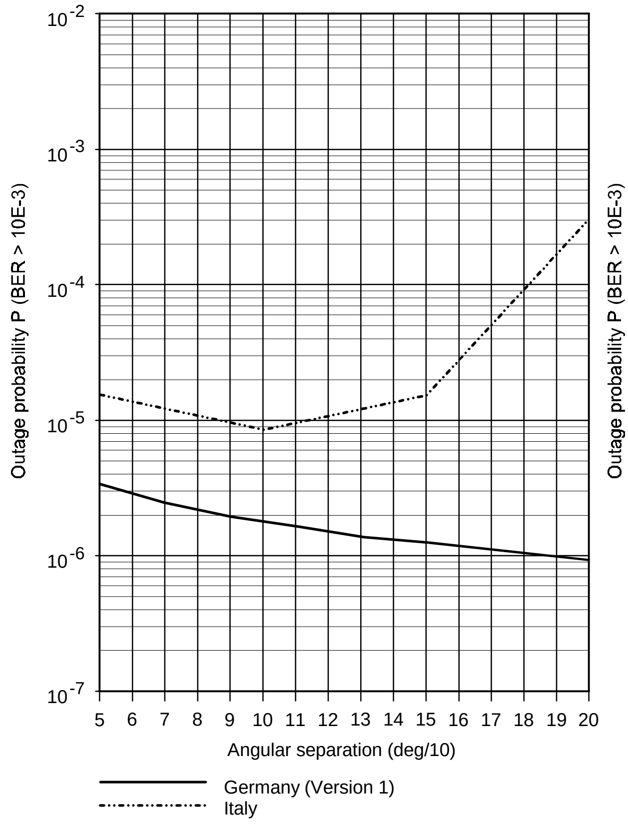

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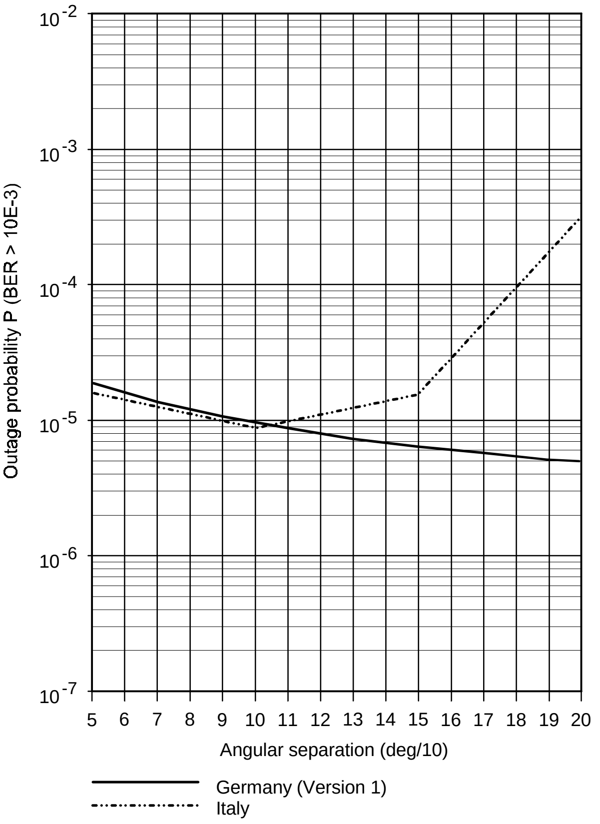

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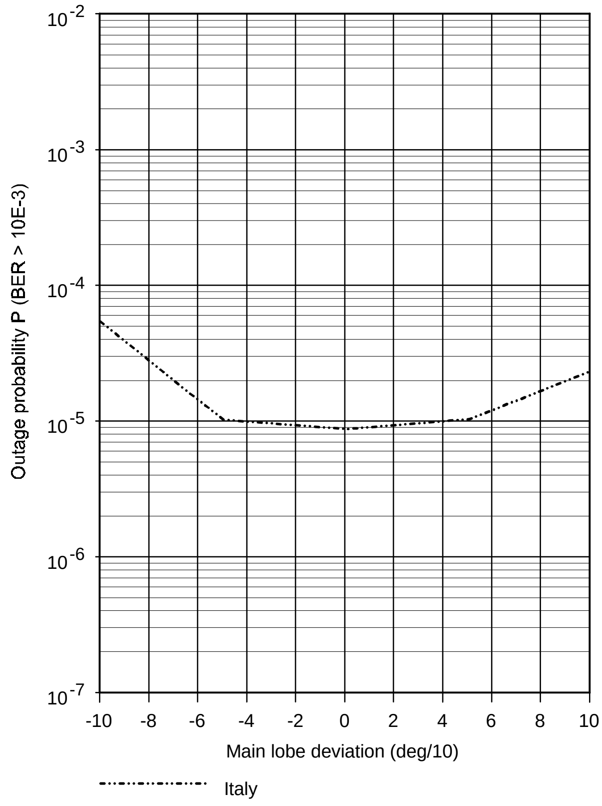

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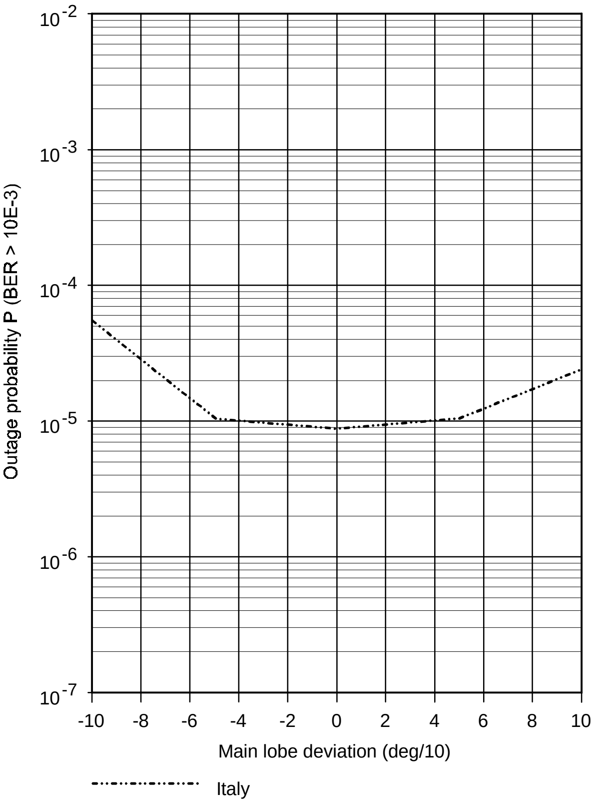

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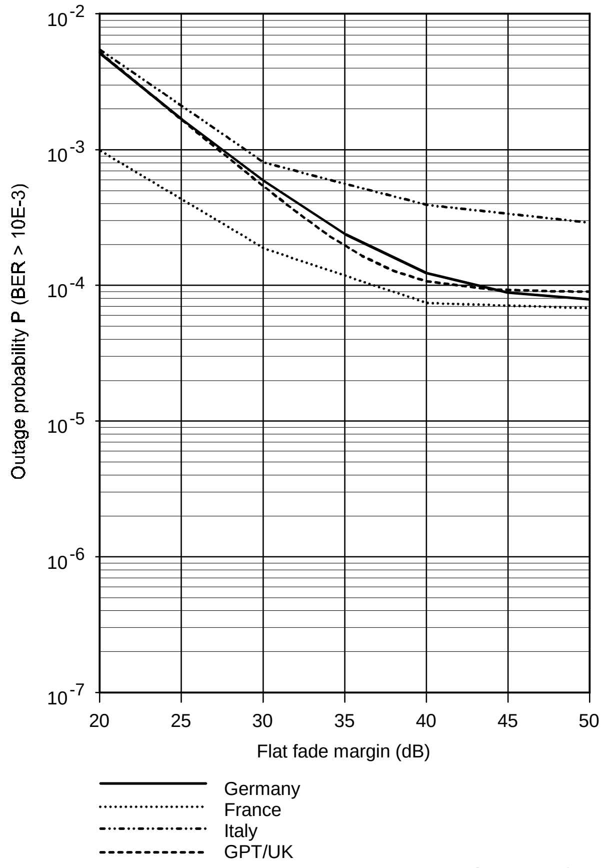

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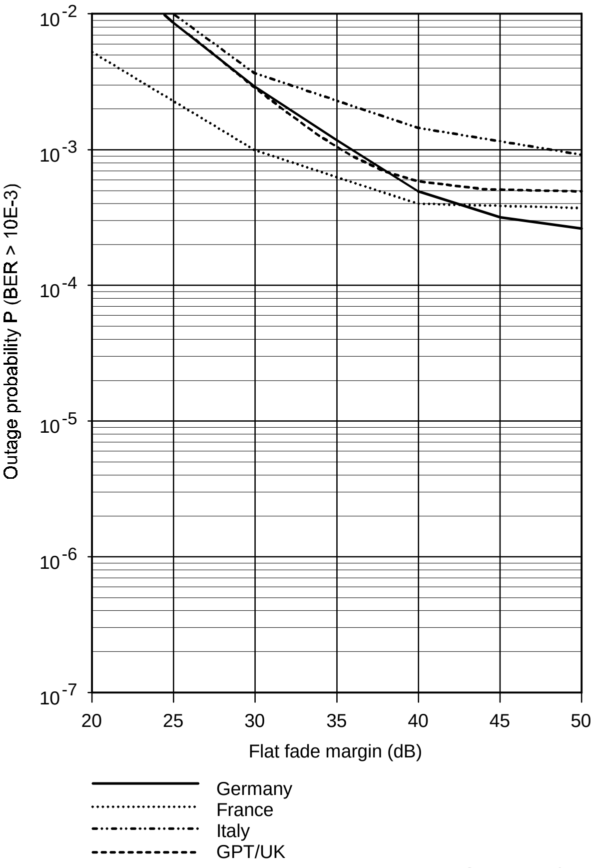

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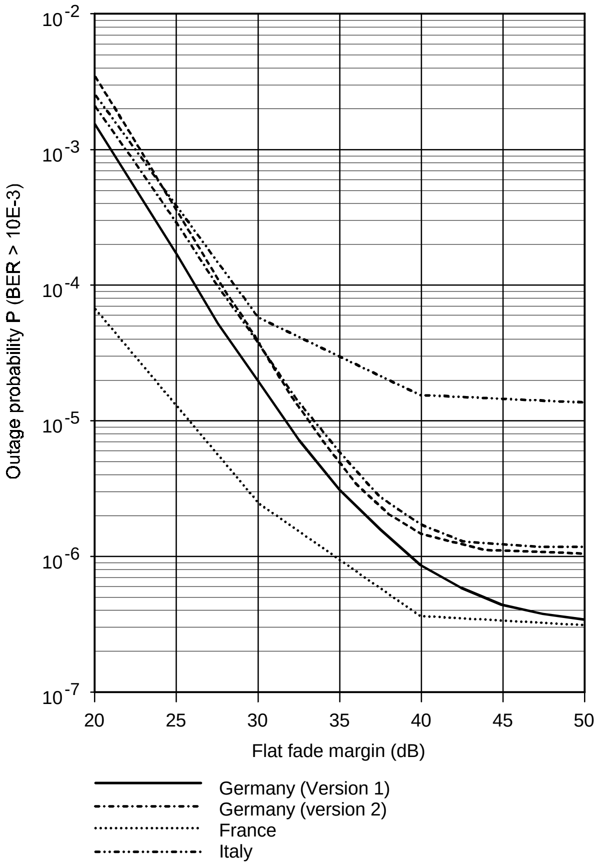

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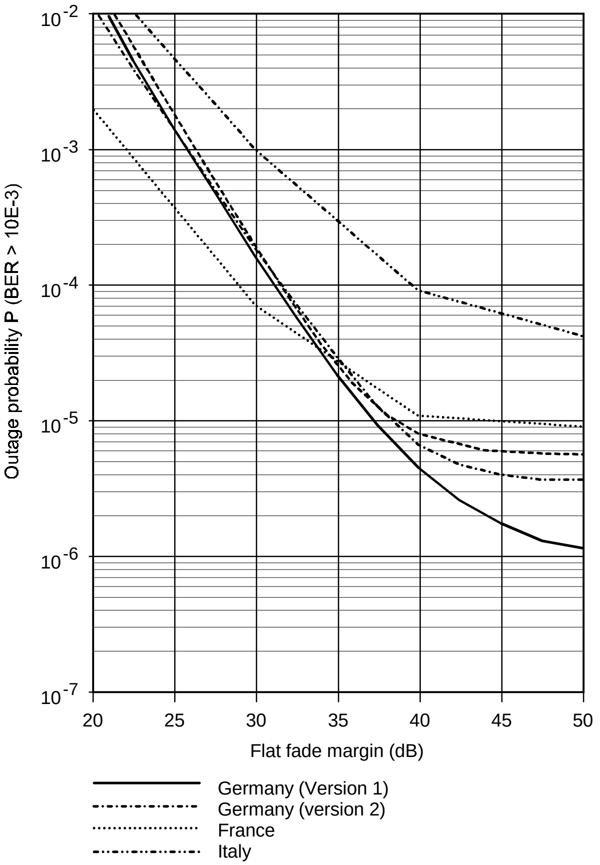

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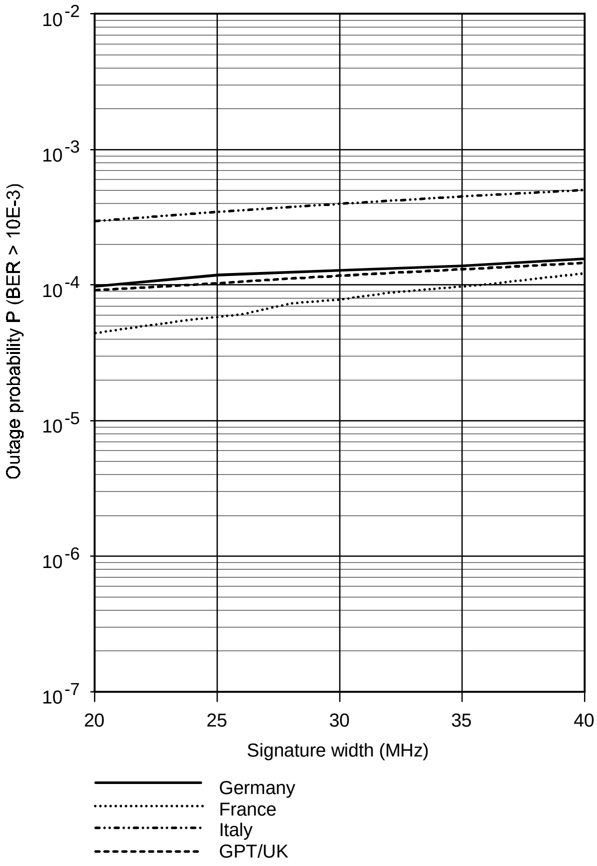

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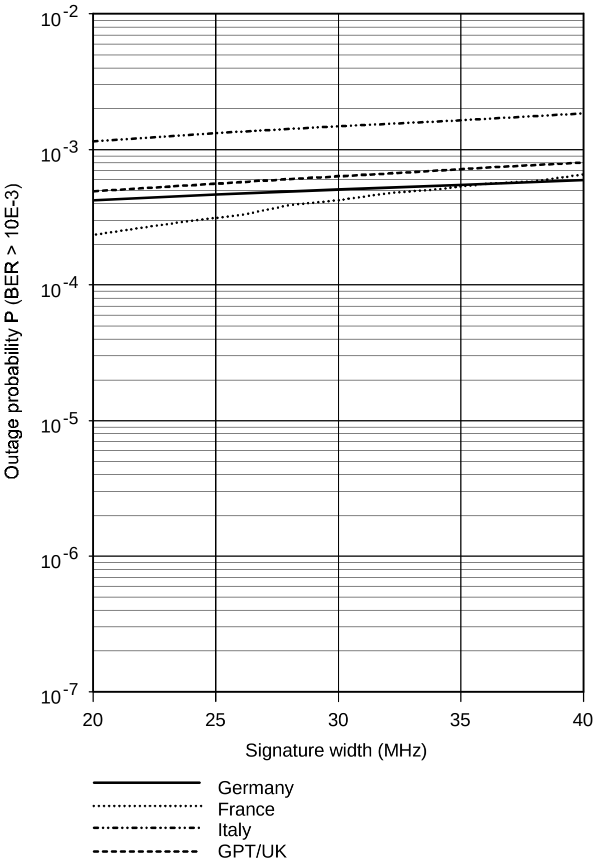

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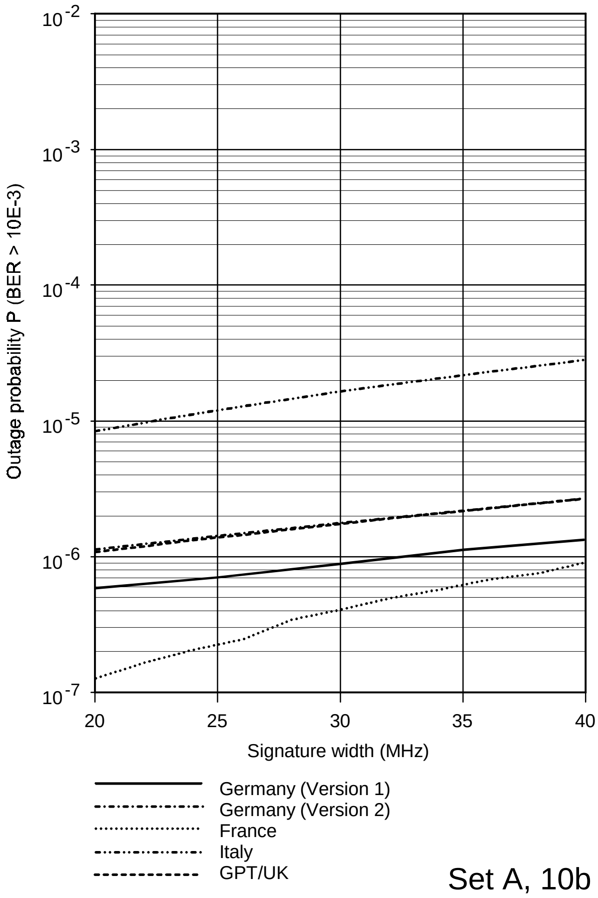

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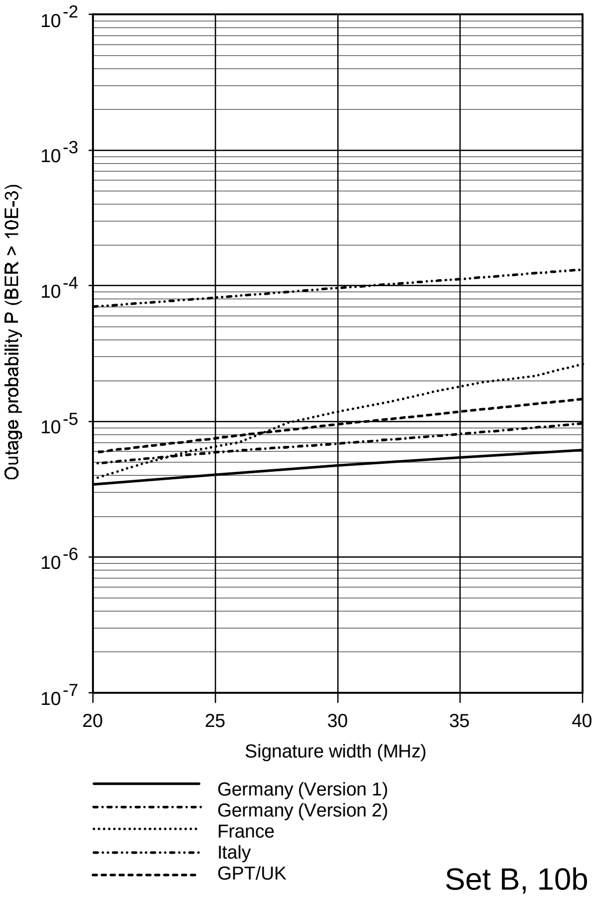

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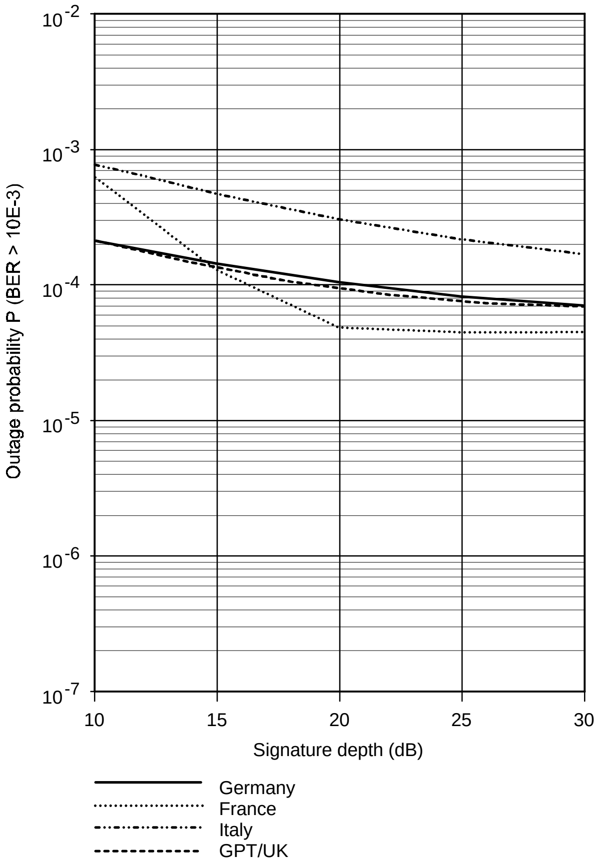

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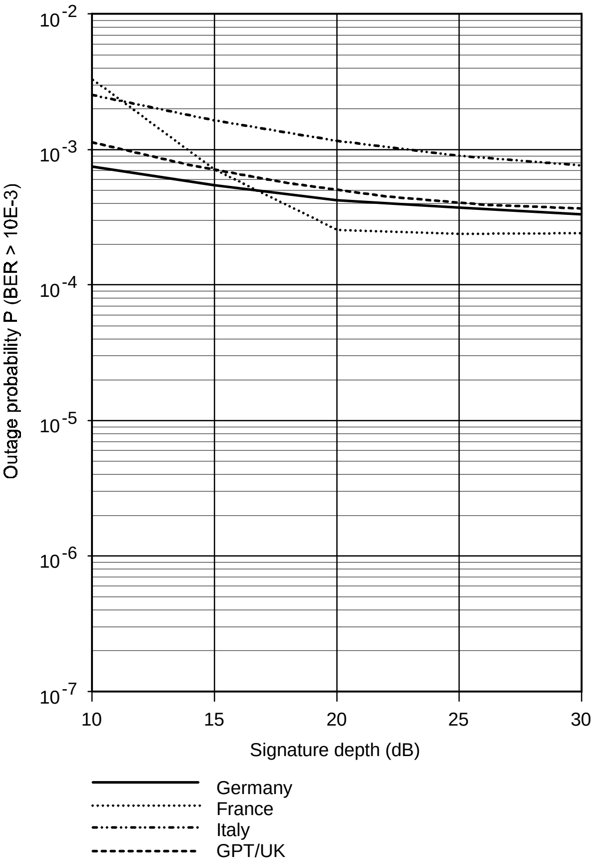

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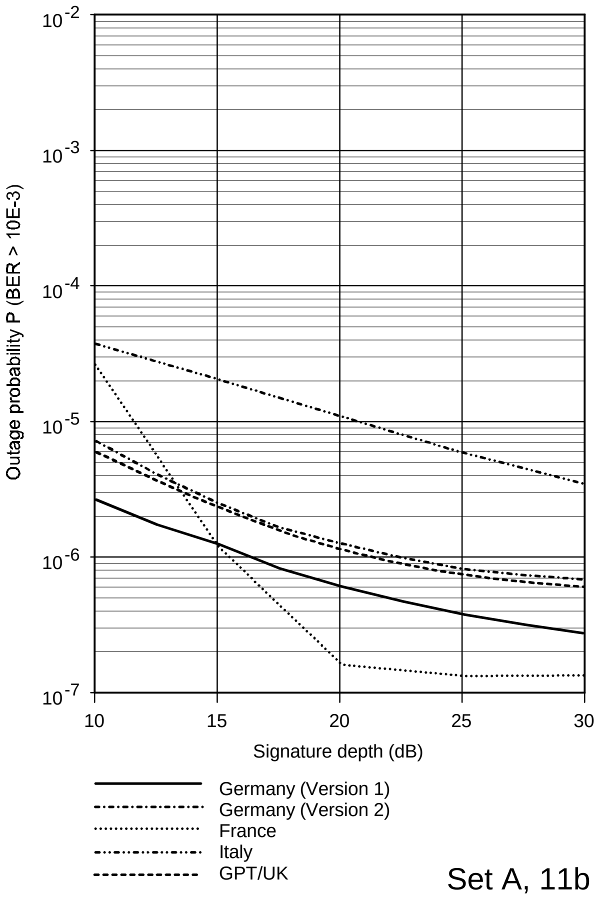

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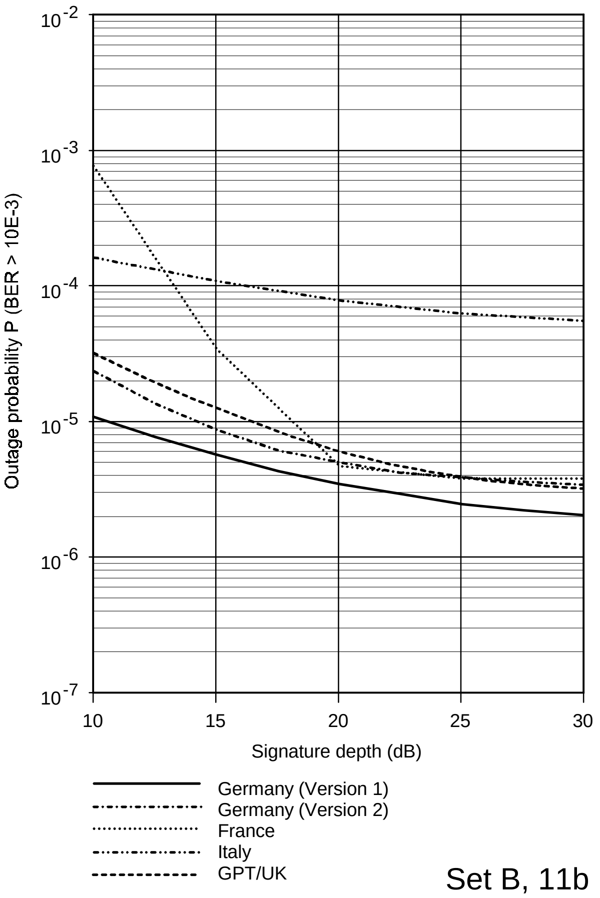

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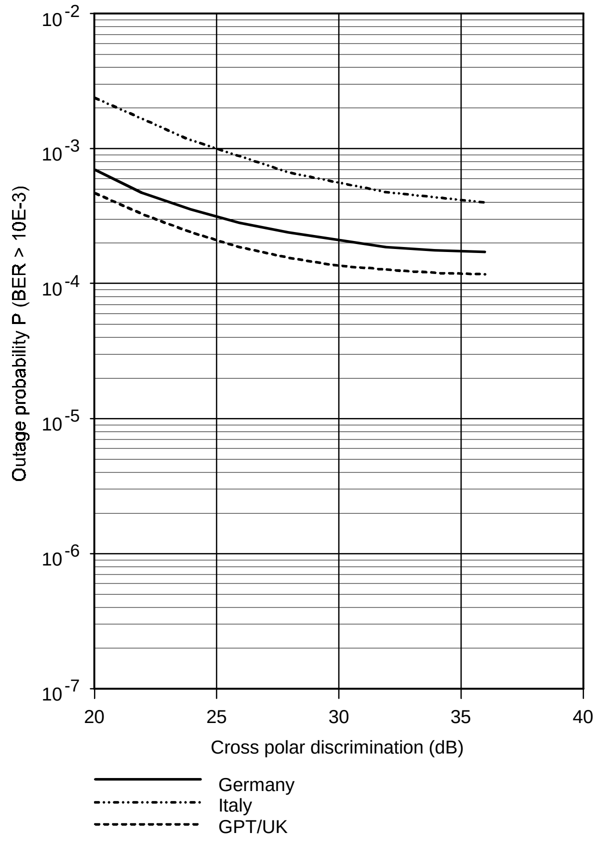

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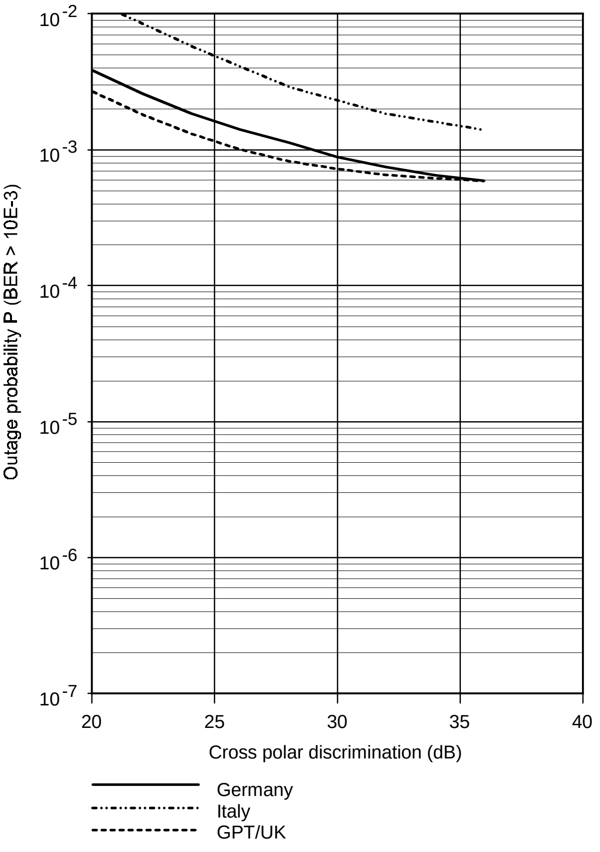

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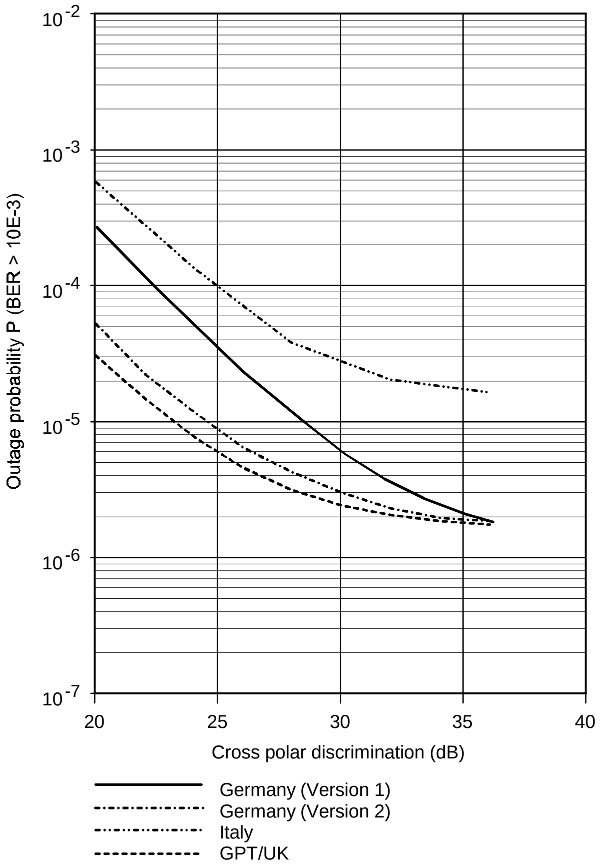

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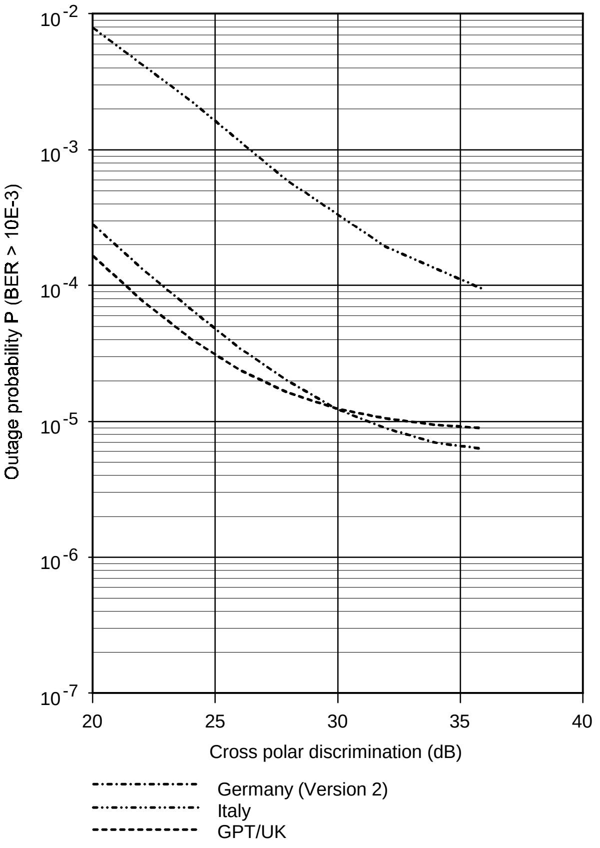

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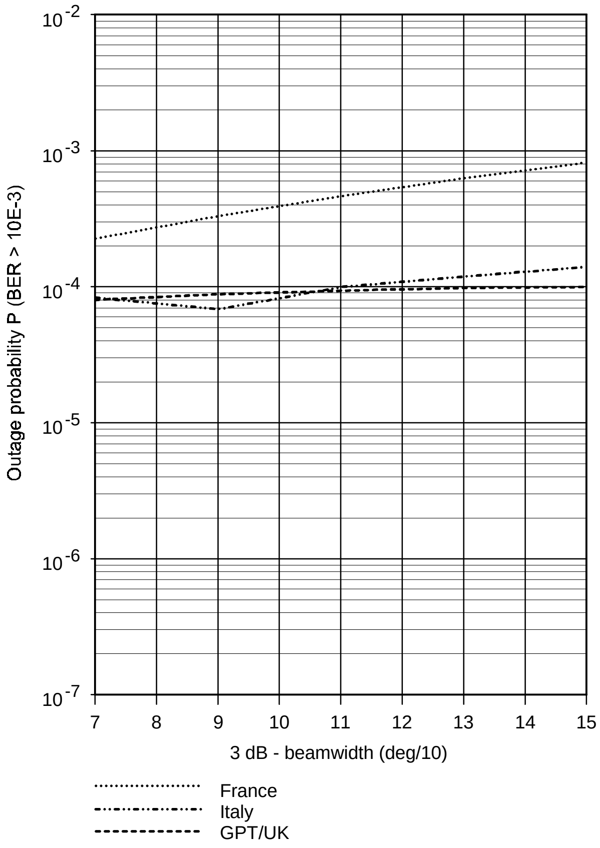

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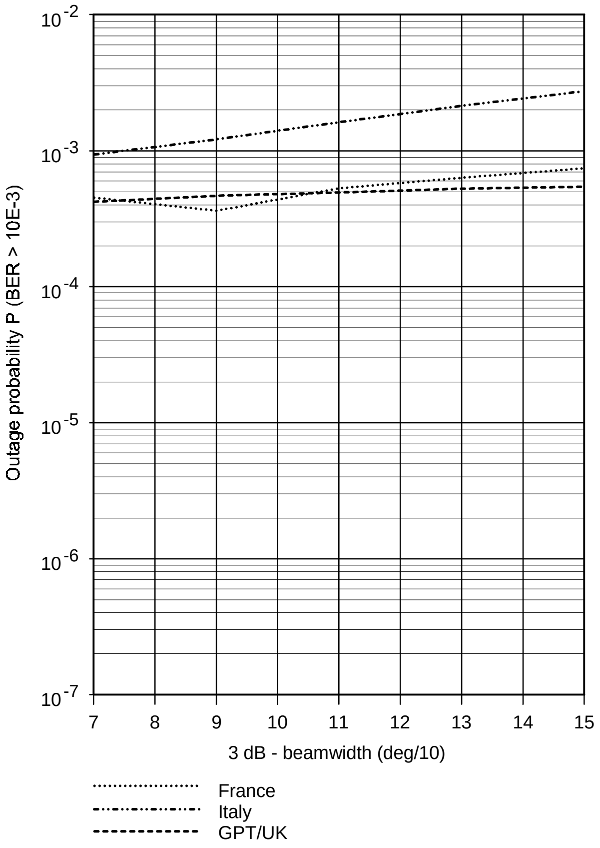

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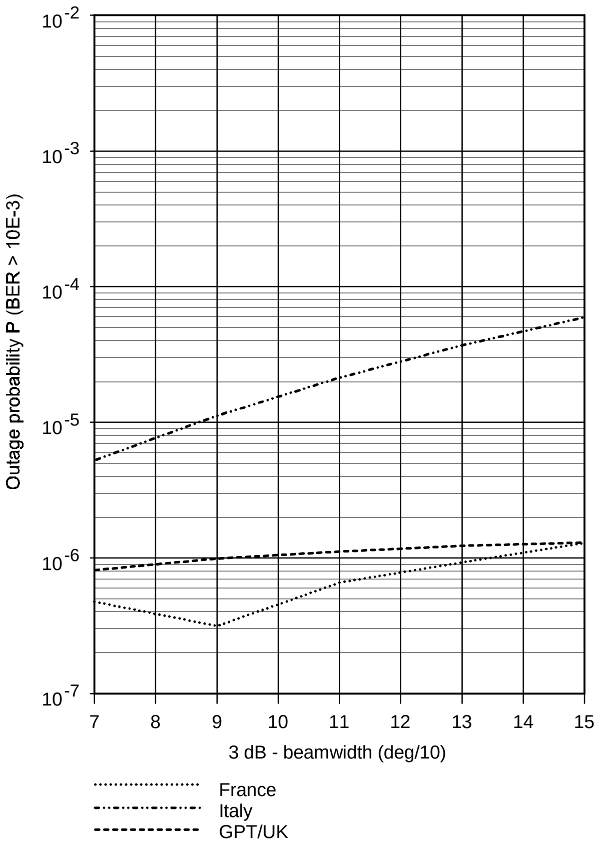

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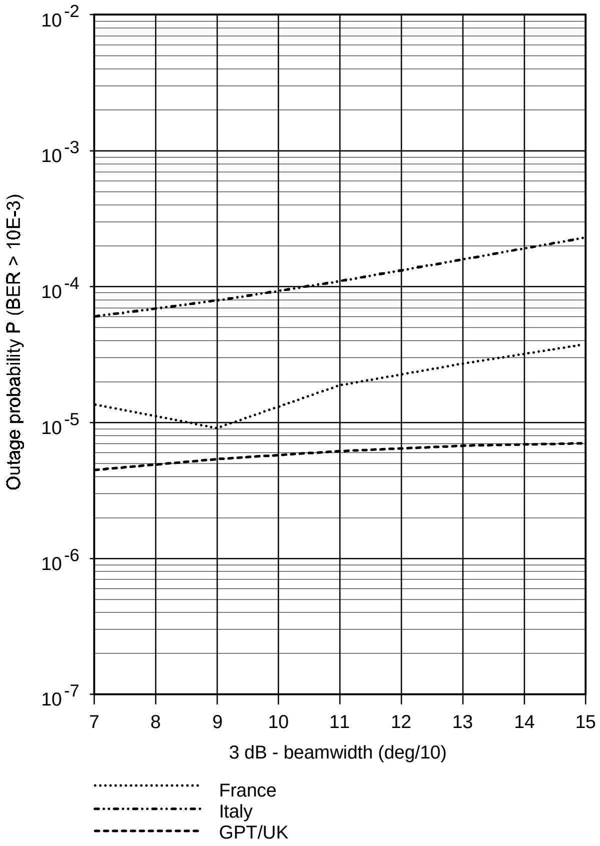

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Annex A:
Description of the performance prediction model submitted by Germany

A.1 Introduction

This annex provides a description of the performance prediction model that has been developed in Germany.

The performance prediction model is based on a new channel model which is described in clause A.2 of this annex. This channel model relies on the well-known and generally accepted assumption of two-ray multipath propagation. However, the probability density functions proposed for the parameters of the channel model are significantly different to those used in other models. These density functions are chosen to allow for physical rationalised interpretations, as well as for an implicit handling of minimum and non-minimum phase channel situations.

Clause A.3 explains the outage prediction for the single-channel configuration. The outage prediction makes use of the new channel model mentioned above in conjunction with the signature concept.

Clause A.4 is devoted to the outage prediction for diversity-channel configurations, with two different approaches.

Additional details on the performance prediction model can be found in [A1] and [A2].

A.2 Description of the single-channel model

It is well known that the transmission channel between the antennas of the transmitter and the receiver of a radio-relay system may diverge from its normal propagation conditions for short periods of time and experience detrimental propagation effects. In well engineered paths with adequate clearance and in the absence of specular reflections, these unwanted effects are mainly due to multipath propagation caused by irregular variations in the refractive index of the air. In the following, after a short discussion on normal propagation conditions, the multipath propagation effects will be modelled by a two-ray model with suitable statistical assumptions.

A.2.1 Normal propagation conditions

Under normal propagation conditions, the receive level is subject to only slight fluctuations of a few decibels peak-to-peak, which can be described by the lognormal distribution. These fluctuations practically have no harmful effect on the system performance as long as the fade margin has been chosen high enough.

A.2.2 Flat fading due to multipath propagation

In periods of significant fading activity, the rapid fluctuations in the receive level, which are described above, are masked by slowly changing and non-selective fading. The following equation is the standard method generally used for channel modelling in this instance:

$$r(t) = g \cdot e^{j\theta} \cdot s(t - \tau) \qquad (2\text{-}1)$$

The transmit signal s(t) appears at the receiver as a receive signal r(t) which, apart from a delay τ, is equivalent to the transmit signal, weighted with a complex transfer factor of amplitude g and phase θ. The parameters g, θ, and τ change relatively slowly over time and are modelled as random variables.

The probability density function of g is taken as Rayleigh, and that of θ as uniform over 2π:

$$
\begin{aligned}
pdf_g(g) &= \frac{2g}{\sigma^2}\exp(-(g/\sigma)^2), \quad g \geq 0; \\
&= 0, \qquad \textit{elsewhere.} \quad E\left\{g^2\right\} = \sigma^2.
\end{aligned}
\tag{2-2}
$$

$$
\begin{aligned}
\mathrm{pdf}_\theta(\theta) &= \frac{1}{2\pi}, \quad -\pi \leq \theta \leq +\pi; \\
&= 0, \qquad \text{elsewhere.}
\end{aligned}
\tag{2-3}
$$

Furthermore, g and θ are statistically independent.

The observed Rayleigh distribution of g agrees with the test results obtained in numerous studies into single-frequency fade distribution. Where fading activity is significant, the measured cumulative distribution of the fading depth can be approximated by a distribution running parallel to a Rayleigh distribution.

A.2.3 Frequency-selective fading due to multipath propagation

The model (2-1) discussed above represents a first approximation to describing the complex propagation mechanisms involved. It can provide useful results for narrowband signals. In periods of abnormal propagation, however, the transmission channel is subject to disturbances which, in the case of wideband transmission, result in linear, time-variant distortion of the transmitted signal. In general, however, the atmospheric phenomena producing these distortions change only relatively slowly, so that it is possible to measure time-variant channel transfer functions H(jω).

According to the two-ray model, the receive signal is:

$$r(t) = g_0 \cdot e^{j\theta_0} \cdot s(t-\tau_0) + g_1 \cdot e^{j\theta_1} \cdot s(t-\tau_1). \tag{2-4}$$

Equation (2-4) can be used to derive the channel transfer function H(jω) if s(t) is replaced by exp(jωt). In this case,

$$H(j\omega) = g_0 \cdot \exp(j(\theta_0 - \omega\tau_0)) + g_1 \cdot \exp(j\theta_1 - \omega\tau_1)). \tag{2-5}$$

From this the familiar form of the channel transfer function for the general two-ray channel model may be derived:

$$H(j2\pi\Delta f) = a \cdot (1 - b \cdot \exp(-j2\pi\Delta f\tau)) \ , \tag{2-6}$$

where:

a: the flat fade parameter;
b: the relative echo amplitude;
Δf: the offset of notch frequency f_0; and
τ: the delay difference.

These four parameters can be derived from the six primary model parameters in (2-5). The relationships are as follows:

$$a = g_0 \cdot \exp(j(\theta_0 - \omega\tau_0)) \tag{2-7}$$

$$b = g_1 / g_0 \tag{2-8}$$

$$\tau = \tau_1 - \tau_0 \tag{2-9}$$

$$\theta = \theta_1 - \theta_0 = \pi + 2\pi f_0 \tau \tag{2-10}$$

$$\Delta f = f - f_0 \tag{2-11}$$

A.2.4 The statistics of the model parameters

A.2.4.1 Probability density function for the delay difference τ

Experimental and theoretical results suggest that the delay difference τ defined in (2-9) may be approximated by the Gaussian probability density function

$$\mathrm{pdf}_\tau(\tau) = (\upsilon\sqrt{2\pi})^{-1} \cdot \exp(-(\tau-\mu)^2/(2\upsilon^2)), \qquad (2\text{-}12)$$

with mean μ and variance υ 2 for the delay difference τ.

A.2.4.2 Probability density function for the relative echo amplitude b

The relative echo amplitude b is the ratio g_1/g_0 of two random variables, see (2-8). A simple expression for its distribution exists if both g_1 and g_0 are Rayleigh-distributed. The Rayleigh-over-Rayleigh distribution function is:

$$\begin{aligned} \mathrm{pdf}_b(b) &= \frac{2}{\beta}\cdot\frac{b/\beta}{((b/\beta)^2+1)^2}\ , && b \geq 0, \quad \beta = \sigma_1/\sigma_0; \\ &= 0\ , && \text{elsewhere.} \end{aligned} \qquad (2\text{-}13)$$

The density parameter β is derived from the density parameters in the distribution functions of g_0 and g_1. With:

$$E\{g_1{}^2\} = \sigma_1{}^2$$

and

$$E\{g_2{}^2\} = \sigma_2{}^2\ ,$$

is given by

$$\beta = \sigma_1/\sigma_2\ . \qquad (2\text{-}14)$$

A.2.4.3 Probability density functions for the flat fade parameter a and the notch frequency offset

The complex flat fade parameter a is defined in (2-7). Its magnitude is thus Rayleigh-distributed in the same way as g_0. The phase is a linear function of the frequency, with the zero phase angle θ_0 distributed uniformly over 2π and the gamma-distributed τ_0.

The phase angle θ in (2-10) is distributed uniformly over 2π in the same way as θ_0 andθ_1. Hence Δf in (2-11) is also distributed uniformly but conditioned in τ:

$$\begin{aligned} \mathrm{pdf}_{\Delta f|\tau}(\Delta f|\tau) &= |\tau|\ , && -\frac{1}{2|\tau|} \leq \Delta f \leq +\frac{1}{2|\tau|}; \\ &= 0\ , && \text{elsewhere.} \end{aligned} \qquad (2\text{-}15)$$

The distribution of the notch frequency offset (Δf) can be assumed to be centred relative to the centre of the channel.

A.3 Outage prediction for the single-channel configuration

Multipath propagation gives rise to two kinds of signal degrading effects, i. e. flat fading and selective fading. The flat fading effect is due to thermal noise and interference. Certainly, both flat and selective fading typically occur in combination. Nevertheless, it seems to be both allowed and advantageous to compute the outage probabilities P_F due to flat fading and P_S due to selective fading separately and to add the results for derivation of the total outage probability P_{tot} , i. e.:

$$P_{tot} = P_F + P_S \ . \qquad (3\text{-}1)$$

The advantages of separate computation of outage due to selective fading and flat fading are:

a) it is very easy to include the effect of thermal noise and flat fading-dependent interference in the outage computation; and

b) in case of diversity operation, a split model can be used which allows different correlation coefficients for the introduction of selective and flat fading between main and diversity channels.

A.3.1 Outage probability due to flat fading

A.3.1.1 Occurrence of flat fading due to multipath propagation

Deep flat fading is assumed to follow the Rayleigh distribution. For fading attenuation F which is above about 15 dB, the following relation holds:

$$P_F = P_0 \cdot 10^{-F/10} \ , \qquad (3\text{-}2)$$

where:

F: fade depth in dB;

P_F: relative percentage of time in which the attenuation exceeds F dB;

P_0: proportionality factor which describes the frequency of occurrence and the deepness of multipath fading events and may depend, inter alia, from the radio frequency and the hop length.

Wherever possible, P_0 should be derived from link-specific measurement results. If such results are not available, empirical formulas have to be used. The following formula is suggested for hop planning within Germany:

$$P_0 = 1{,}4 \cdot 10^{-8} \cdot f \cdot d^{3{,}5} \ ;$$

with:

f: transmission frequency in GHz;

d: hop length in km.

Other formulas can be found in the documentation of ITU-R Study Group 3.

A.3.1.2 Influence of thermal noise

In a system with fade margin MF and a normal carrier-to-noise ratio $(C/N)_N$, the actual carrier-to-noise ratio as a function of fade depth F is:

$$C/N = (C/N)_N - F \ . \qquad (3\text{-}3)$$

Since:

$$\mathrm{MF} = (\mathrm{C/N}) - (\mathrm{C/N})_0 \ ,$$

we obtain

$$\frac{\mathrm{C}}{\mathrm{N}} = (\mathrm{C/N})_0 + \mathrm{MF} - \mathrm{F}\ ; \qquad (3\text{-}4)$$

$(C/N)_0$: C/N at system threshold, defined by outage or specific quality criteria (e. g. BER = 10^{-3} for severely errored seconds), modulation scheme and equipment properties.

A.3.1.3 Influence of interference

Each receiver is exposed to a number of interfering signals having different sources, effects on BER, and fading dependencies. In the following, we calculate the effects of the most important interferers:

- adjacent channel co/crosspolar;
- co-channel crosspolar (without/with XPIC);
- adjacent hops, co-channel (without/with ATPC);

assuming the worst-case conditions:

- all interferers have a noise-like effect on BER;
- all interferers are summed using power law addition;
- all interferers are unaffected while the interfered signal fades.

Then, the carrier-to-noise ratio with respect to the j-th interferer of J interfering signals is:

$$\left(\frac{C}{I}\right)_j = IRF_j + XPD_j + AHD_j - F\ , \qquad (3\text{-}5)$$

with:

IRF: interference reduction factor between adjacent channels due to spectrum shape and filter response;

XPD: crosspolar discrimination.

$$\mathrm{XPD} = \mathrm{XPD}_0 + \mathrm{Q} + \Delta\mathrm{XPIC}.$$

XPD_0 + Q is the asymptotic XPD of the hop, typically 40 dB to 50 dB.

ΔXPIC is the improvement of co-channel crosspolar C/I due to crosspolar interference cancelling.

ADH: adjacent hop decoupling resulting from angular discrimination of antennas, different path losses and transmitting power levels, and the improvement due to Adaptive Transmitting Power Control (ATPC).

A.3.1.4 Joint influence of thermal noise and interfering signals

The joint influence of noise and interference can be described conservatively by a resultant carrier-to-(noise + interference) ratio given by:

$$\frac{C}{N + \sum_j I_j} = \frac{C}{N} + 10 \cdot \lg\left(1 + \sum_{j=1}^{J} 10^{\frac{C/N - (C/I)_j}{10}}\right)\ , \qquad (3\text{-}6)$$

where C/N is given by equation (3-4) and $(C/I)_j$ by equation (3-5).

The only statistical property of the channel, which is of importance in this context, is the Rayleigh-distributed flat fading attenuation given by (3-2).

Having described the dependence of carrier-to-noise ratio (C/N) and carrier-to-interference ratio (C/I) as a function of fading, it is now easy to derive an expression for the outage probability due to flat fading. As will be shown, the respective expression contains the effects of both noise and interference and can be factorized to show the influence of both effects separately.

Under fading conditions, the system can be operated down to:

$$\frac{C}{N + \sum_{j} I_{j}} = \left(\frac{C}{N}\right)_{0} \quad . \tag{3-7}$$

Hence, from equations (3-4) to (3-6), and after insertion into equation (3-2), an expression for the outage probability (or the relative outage time) due to flat fading is obtained:

$$P_F = P_0 \cdot \left(10^{-\frac{MF}{10}} + 10^{\frac{\left(\frac{C}{N}\right)_0}{10}} \cdot \sum_{j=1}^{J} 10^{-\frac{IRF_j + XPD_j + AHD_j}{10}} \right), \tag{3-8}$$

which is the sum of two additive terms representing the influence of:

- thermal noise, which depends on system fade margin MF;
- the sum of all interfering signals which depends on the respective IRFj, the cross-polar discrimination factor XPDj (including XPIC gain), and the adjacent hop decoupling AHDj (including antenna discrimination, ATPC gain).

A.3.2 Outage probability due to selective fading

The method described here is based on the channel model described in clause A.2 in conjunction with the signature concept.

A.3.2.1 Approach

The procedure is to calculate the probability that the multipath fading channel will cause the selective notch to lie below the locus of points generating the system outage signature. System outage may be defined by the occurrence of a Bit Error Ratio (BER) ≥ 10^{-3} or some other quality criteria. The system outage signature, weighted with the statistics of the multipath fading model, is integrated to yield a statistic probability for the occurrence of outages.

The probability derived in this way is conditioned on the occurrence of multipath fading. Therefore, this probability has to be multiplied by a constant representing the fraction of time where the channel is in the fading condition to finally yield the unconditional outage probability.

In this procedure, dynamic effects and thermal noise and interferences are not considered. With regard to the latter, the approach remains valid within a wide range of signal power levels. However, as the signal power level approaches the system threshold, the noise in the system causes additional outage, which can be taken into account by incorporating the flat fade parameter into the calculation procedure.

A.3.2.2 Integration over the outage region

According to subclause A.3.1, the outage probability due to frequency selective fading on condition of multipath fading (MPF) is:

$$\Pr\left\{ outage \middle| MPF \right\} = \int_{\Omega} pdf_{\Delta f, b, \tau | MPF}\left(\Delta f, b, \tau \middle| MPF\right)\, d\Delta f\, db\, d\tau \ , \tag{3-9}$$

where outage region Ω is determined by the signature depending on τ. The joint distribution function is the product of the individual functions:

$$pdf_{\Delta f,b,\tau|MPF}(\Delta f,b,\tau) = pdf_{\Delta f|\tau}(\Delta f|\tau)\cdot pdf_b(b)\cdot pdf_\tau(\tau)\ . \tag{3-10}$$

By restricting the distribution for the relative echo amplitude to the Rayleigh-over-Rayleigh type, and after some approximation, one can obtain a practical expression for the probability of the outage due to selective fading:

$$\Pr\{outage|MPF\} = 2\cdot\left(\frac{\beta}{1+\beta^2}\right)^2\cdot\left[W(b_N-b_M)/\tau_{ref}\right]\cdot\left(\mu^2+\upsilon^2\right)\ . \tag{3-11}$$

We distinguish there different types of impact parameters, those characterising the equipment, those characterising the transmission medium and those depending on the hop geometry.

The equipment is characterised by its signature in terms of the parameters:

W: the width of the signature;

b_N: upper bound of the critical notch depth of the rectangular signature approximation in a non-minimum phase channel condition, measured (or calculated) at a reference path delay difference τ_{ref};

b_M: lower bound of the critical notch depth of the rectangular signature approximation in a minimum phase channel condition, measured (or calculated) at the same reference path delay differenceτ_{ref} as above.

As such, the term $W(b_N - b_M)/\tau_{ref}$ is the linear scaled area of the signature at a reference delay τ_{ref}, divided by that delay.

The transmission medium is characterized by the statistics of the relative echo amplitude and the path delay difference, where the latter one implicitly also depends on the hop geometry.

The statistical value of the relative echo amplitude is determined by its density parameter β In the absence of any hop specific information, a value of $\beta = 1$ is used. Note that $\beta = 1$ represents a worst case condition.

The statistic of the path delay difference is characterised by its mean μ and its variance μ^2 and depends on the hop geometry because:

$$\mu = u/c$$

and

$$\upsilon^2 = 2\cdot d\cdot(\upsilon')^2\ ,$$

where:

- u is the mean path length difference;
- c is the speed of light;
- d is the hop length; and
- υ is the variance of the delay per unit path length.

In the absence of any hop-specific information, we use:

$$\mu = 0{,}7\frac{d/km}{50}\ ns\ ,$$

$$\upsilon^2 = 0{,}49\frac{d/km}{50}\ ns^2\ .$$

In order to arrive at the unconditioned outage probability:

$$\begin{aligned} P_S &= \eta \cdot \Pr\left\{ outage \middle| MPF \right\} \\ &= \eta \cdot 2 \cdot \left(\frac{\beta}{1+\beta^2} \right)^2 \cdot \left[W\left(b_N - b_M \right) / \tau_{ref} \right] \cdot \left(\mu^2 + \upsilon^2 \right) , \end{aligned} \tag{3-12}$$

we need the a priori probability η that multipath propagation is occurring. Following [A3], we use the estimate:

$$\eta = 1 - \exp\left(-0{,}2 \cdot P_0^{3/4} \right) , \tag{3-13}$$

where P_0 is the proportionality factor used in (3-2).

A.4 Outage prediction for diversity configurations

A.4.1 Description of diversity reception

The outage probabilities of the unprotected single channel can be reduced significantly if the information to be transmitted is simultaneously received over two (or more than two) distinct paths (diversity reception).

The paths may be separated by space, angle, or frequency. After reception, the signals of the two paths are combined and evaluated in an appropriate way.

Each of the diversity paths may be regarded as a single channel of its own which can be described by a statistical two-ray model with the random variables a, b, Δf and τ, see (2-6). According to subclause A.2.1, these random variables are defined by their probability density functions and the corresponding density parameters.

The density functions are identical for both paths. The density parameters are identical, too, if both paths are of the same kind; for example, this is in general the case with frequency diversity. However, if both paths exhibit different characteristics (e.g. this may be the case with angle diversity, where the antenna beam pointing towards the ground will preferably experience deeper fadings than the upper antenna beam), different density parameters have to be used.

The reduction of outage probability by applying diversity reception is based on the fact that the fading characteristics of the two paths are un-correlated at least partially, but more often to a great extent. In principle, this could be modelled by introducing correlations between the random variables of both paths. In this way, a diversity channel model could be defined. However, this procedure is not followed here, because many different correlation relations have to be examined, and the finally desired outage probability could be estimated only by extensive computer simulations.

Instead, it seems much clearer and simpler not to consider the correlations between the random variables, but to look at the correlations between the outages in the single paths. Then, the calculation of outage probability P_D with diversity reception can follow the scheme given by Mojoli and Mengali in [A4]. In the following, the main steps of this scheme are summarized and commented.

According to this scheme, at first only time periods with MultiPath Fading (MPF) and the corresponding conditioned outage probabilities are considered. It is assumed, that these periods coincide in both diversity paths.

If we neglect any gain which may be achieved by an appropriate combining of the diversity signals, then the conditioned outage probability with diversity reception is equal to the conditioned joint probability of a simultaneous outage of both channels 1 and 2, i.e.:

$$P_D\left(outage \middle| MPF\right) = P\left(outage\ ch1,\ outage\ ch2\ \middle|\ MPF\right)\ . \tag{4-1}$$

The outages of channel 1 and channel 2 are assumed to be correlated with correlation coefficient K^2. Then, if the conditioned outage probabilities of the single channels are not too large and if K^2 is not too close to 1, the following approximation holds:

$$P_D\left(outage \middle| MPF\right) = \frac{P(outagech1 | MPF) \cdot P\left(outagech2 \middle| MPF\right)}{1 - K^2}\ . \tag{4-2}$$

If $K^2 = 0$, i. e. if the outages are un-correlated, the conditioned outage probability with diversity reception is therefore given by the multiplication of the conditioned outage probabilities of the single channels, which is self-evident. If K is very close to 1, then (4-2) is no longer valid. In this case, the single channel outages are almost totally correlated, and the conditioned outage probability with diversity reception is equal to the conditioned outage probability of the unprotected single channel.

The unconditioned outage probabilities with diversity as well as with single channel reception follow from the corresponding conditioned probabilities by multiplication with the a-priori probability η that multipath propagation is occurring:

$$\begin{aligned} P_D &= P_D\left(outage\right) = \eta \cdot P_D\left(outage \middle| MPF\right)\ , \\ P_1 &= P\left(outage\ ch1\right) = \eta \cdot P\left(outage\ ch1 \middle| MPF\right)\ , \\ P_2 &= P\left(outage\ ch2\right) = \eta \cdot P\left(outage\ ch2 \middle| MPF\right)\ . \end{aligned}$$

Insertion of these relations in (4-2) yields:

$$P_D = \frac{1}{\eta\left(1 - k^2\right)} \cdot P_1 \cdot P_2\ . \tag{4-3}$$

If both single channels are of the same kind and the outage probabilities are equal, i.e.:

$$P_1 = P_2 = P\ ,$$

we get the result:

$$P_D = \frac{1}{\eta\left(1 - K^2\right)} \cdot P^2\ . \tag{4-4}$$

It is worthwhile to note, that with un-correlated single channels ($K^2 = 0$) the expression:

$$P_D\Big|_{K^2=0} = \frac{1}{\eta} \cdot P^2 \tag{4-5}$$

is valid and not $P_D = P^2$. According to (4-5), the expression $P_D = P^2$ is only correct, if $\eta = 1$ holds, i. e. if the transmission channel is affected by multipath propagation during the whole time of interest.

The effectiveness of diversity reception with respect to the reduction of outage probability can formally be described by an improvement factor I which is implicitly defined by:

$$P_D = \frac{P}{I}\ . \tag{4-6}$$

A comparison of this definition with (4-4) finally leads to:

$$I = \frac{\eta\left(1 - K^2\right)}{P}\ . \tag{4-7}$$

Estimated expressions for the correlation coefficient K^2 and the improvement factor I, respectively, are presented in subclauses A.4.2 and A.4.3.

There are two possible approaches to evaluating the outage probability for diversity reception, P_D. These approaches will be explained in the following subclauses A.4.2 and A.4.3.

A.4.2 Outage prediction: Approach 1

Approach 1 calculates P_D by using mathematical expressions for the correlation or un-correlation, respectively. This is done for the different diversity methods: space diversity, frequency diversity, and angle diversity. The same procedure is used to evaluate P_D for combinations of the above mentioned methods and for higher order diversity systems.

A.4.2.1 Environmental conditions

Multipath probability, η [A4] is the most important parameter as far as diversity protection is concerned, and it is related to deep fade occurrence factor P_0 [A4].

Average delay T_a, i.e. expected value $<T_a>$, or second order moment $<T^2>$, of the relative delay between the rays is extremely important to determine outage probability P of the unprotected channel. Independent of the value of P, the delay dispersion has direct influence on correlation k, between two channels in frequency or angle diversity arrangements.

A secondary fading parameter exists, in addition to the primary parameters P_0, η, T_a listed above. This parameter is deep fade occurrence factor conditioned by multipath, $P_0 | MP$. $P_0 | MP$ is useful to compute conditioned outage probability $P | MP$. The computation of diversity protections, especially those of order higher than 2 is easier if conditional probabilities are used [A4].

A.4.2.1.1 Deep fade occurrence factor (P_0)

Evaluate the probability to exceed deep fades by the asymptote of the fading distribution [A10], [A4]:

$$P(F) = P_0 \cdot 10^{-F/10} \qquad (4\text{-}8)$$

which is fixed by deep fade occurrence factor P_0. The value of P_0 expected for the worst month can be evaluated by:

i) The proposed empirical rule:

P_0 = 0,3 c (f/4) $(d/50)^3$;

d = path length (km);

f = carrier frequency (MHz);

c = ab = terrain coefficients (coefficient c is unity for average rolling terrain);

roughness w = 15 m; b = $(15/w)^{1,3}$ = 1;

continental temperate climate and a = 1.

ii) Any other empirical rule; e.g. for North West Europe:

$$P_0 = 1{,}4 \cdot 10^{-8} \cdot f \cdot d^{3,5} = 0{,}05 \cdot \frac{f}{4} \cdot \left(\frac{d}{50}\right)^{3,5} \; [10]$$

This rule equals rule i) for d= 50 km, a = 1, b = 1/6 (i.e. w = 60 m).

Minor differences appear for path lengths different from 50 km.

iii) From previous experience and measurement on the specific path, if the worst month condition was identified during at least 2 to 3 different years.

Anomalous slopes of P(F) have been rarely observed, while P_0 values significantly different from those of apparently similar paths are less rare events.

Deep fade occurrence factor P_0 is related to fading exceeded 0,1 % of time by:

$$F(0{,}1\%) = 30 + 10 \cdot \log(P_0) \quad \leftrightarrow \quad P_0 = 10^{\left(F(0{,}1\%) - 30\right)/10}$$

Fading F(0,1 %) is sometimes more readable than asymptote $P(F) = P_0 \cdot 10^{-F/10}$. This is particular the case for fading related to the total power of a high speed digital signal, the spectrum of which is broad.

EXAMPLE 1:

Typical NW Europe path d = 50 km,	f = 4 Ghz
rolling terrain, w = 60 m	b ≈ 1/6
continental temperate climate	a = 1
	P_0 = 0,05
	F(0,1 %) = 17 dB

EXAMPLE 2:

Reference path d = 50 km,	f = 4 Ghz
rolling terrain, w = 15 m	b = 1
continental temperate climate	a = 1
	P_0 = 0,3
	F(0,1 %) = 24,8 dB

EXAMPLE 3:

Long overwater path, temperate climate:

d = 150 km; f = 2 GHz	c = 1
	P_0 = 4
	F(0,1 %) = 36 dB

A.4.2.1.2 Multipath probability

Evaluate multipath probability (η) [A4,A12,A14,A15]:

$$\eta = 1 - e^{-0{,}2 \cdot P_0^{0{,}75}} \tag{4-9}$$

EXAMPLE 1:

Reference path:

P_0 = 0,3	η = 0,078

This means that atmosphere is layered for 56 hours during the worst month; as not all days are affected, either nothing or more than 2 hours of multipath are typically present in a day, distributed in one or more periods of time. The duration generally exceeds 20 to 30 minutes. The most probable multipath times are sunset, around midnight, and after sunrise, in clear days.

EXAMPLE 2:

Difficult path:

$P_0 = 10$ $\eta = 0{,}675$

This means that atmospheric multipath is present for the majority of time; some multipath hours shall be expected every day; some days may be continuously affected by multipath.

A.4.2.1.3 Deep fade occurrence factor during multipath

The deep fade occurrence factor during multipath ($P_0|MP$) is computed as [A4]:

$P_0|MP = P_0/\eta$

This figure must be used to compute outage probability conditioned by multipath. Conditional probabilities are particularly useful dealing with diversity protection.

EXAMPLE 1:

Reference path:

$P_0 = 0{,}3 \quad \eta = 0{,}078 \Rightarrow P_0|MP = 3{,}85$

EXAMPLE 2:

Difficult path:

$P_0 = 10 \quad \eta = 0{,}675 \Rightarrow P_0|MP = 14{,}8$

A.4.2.1.4 Average delay of the second atmospheric path T_a = <T> and second order moment of the relative delay $<T^2>$

When the relative delay T exceeds half of the symbol duration, a destructive intersymbol interference is produced. Powerful equalisers are required to counteract this interference. Average delay T_a, of the second atmospheric path was found well correlated to path length:

$$T_a = T_0 \cdot \left(\frac{d}{50}\right)^{\nu} \qquad (4\text{-}10)$$

d = path length (km);

T_0 = 0,7 - 1 ns; and

ν = 1,0 - 1,3.

The above empirical formula for T_a was derived from measured outage seconds, according to a specific model, therefore it must be used in connection with the same model. A simple scaling factor was observed with respect to other models [A4, A14-A16].

The following examples apply for $T_0 = 0{,}7$ ns and $\nu = 1{,}3$:

EXAMPLE 1:

Reference path, 50 km, $T_a = 0{,}7$ ns.

EXAMPLE 2:

Long path, 100 km, $T_a = 1{,}72$ ns.

EXAMPLE 3:

The longest path ever tested, 360 km, T_a = 9,11 ns.

Typical distance between two neighbouring peaks of group delay:

$1/T_a$ = 0,110 GHz = 110 Mhz.

NOTE: Ground reflections can alter significantly the transfer function. A two-ray model is still applicable but the statistic of T should be computed properly. Computer simulations are suggested.

A.4.2.2 Diversity protection

Diversity performance P_{div} can easily be computed starting from non protected channel performance P. The basic law of a protection of N^{th} order is [A4,A14,A15]:

$$P_{div,N} = \frac{P^N}{\eta^{(N-1)} \cdot D(1,2\ldots N)} \qquad \text{4-11)}$$

where

D(1,2...N) = determinant of correlation coefficients k_{ij} between diversity channels 1,2...N.

Computations are simplified by using conditional probabilities:

$$P_{div,N}\big|MP = \frac{P\big|MP^N}{D(1,2\ldots N)} \qquad (4\text{-}12)$$

Obviously the input value (for the unprotected channel) is:

$P\,|\,MP = P/\eta$

while the final (unconditional) output of interest is:

$P_{div,N} = P_{div,N}\,|\,MP \cdot \eta$

The basic law must be used in a recursive way, e.g. for a quadruple diversity between channels (1,2,3,4) also the four different triples (1,2,3); (1,2,4); (1,3,4); (2,3,4) must be examined, plus the six different pairs (1,2); (1,3); (1,4); (2,3); (2,4); (3,4) as well as the four single channels 1; 2; 3; 4. The actual result of interest , P_{div}, is the minimum of $P_{div,4}$, $P_{div,3}$ (four cases), $P_{div,2}$ (six cases), P (four cases).

Computations can be done by hand, as will be shown by numerical examples, however simple computer programs avoid tedious iterations when N > 2.

A.4.2.2.1 Correlation coefficients

a) **Space diversity [A3,A11,A14-A16,A18]:**

$$k_{SD}{}^2 = e^{-0,4 \cdot 10^{-6} \cdot (h/\lambda)^2} \qquad (4\text{-}13)$$

with:

h = vertical antenna spacing;

λ = wavelength.

EXAMPLE 1:

f = 4 GHz ⇒ λ = 0,075 m; h = 15 m;

k_{SD}^2 = 0,852;

D = $(1-k_{SD}^2)$ = 0,148.

b) Frequency diversity [A3,A16]:

$$k_{FD}^2 = e^{-0,9 \cdot \Delta f \cdot T_a} \tag{4-14}$$

with:

Δf = channel spacing

EXAMPLE 2:

Δf = 40 MHz;

d = 50 km ⇒ T_a = 0,7 ns;

k_{FD}^2 = exp(-0,9 · 0,040 · 0,7) = 0,975;

D = $(1 - k_{FD}^2)$ = 0,025;

c) Angle diversity [A17-A21]:

$$k_{AD}^2 = e^{-0,1 \cdot (<\alpha> / \alpha_3) \cdot (\Delta\alpha / \alpha_3)} \tag{4-15}$$

where:

α_3 = semi-lobe width of antenna (gain reduced by 3 dB at this angle);

$\Delta\alpha$= angle diversification between „main" and „diversity" lobes if one angle diversity antenna is used or panning difference between antennas if two different dishes are used;

$<\alpha>$ = applicable average difference between arrival angles of the atmospheric paths during multipath;

$<\alpha>$ = C · (σ / 50) · (d / 50) where C = 0,1 to 0,2 degrees;

σ = standard deviation of the vertical gradient of the radio refractive index;

d = path length (km).

EXAMPLE 3:

d = 50 km; σ = 50 Nunit/km ⇒ $<\alpha>$ = 0,2 degrees; α_3 = 0,43 degrees.

Assuming a pair of tilted antennas and allowing a panning loss of 6 dB one gets:

$$\Delta\alpha = \alpha_3 \cdot \sqrt{6/3} = 0,6 \text{ degr.}$$

k_{AD}^2 = 0,937;

D = $1 - k_{AD}^2$ = 0,063.

A.4.2.2.2 Mixed diversity arrangements

If two RF channels are separated by frequency, height and tilt of the antennas, then [A3]:

i) compute the correlation coefficients due to each effect separately, i.e. k_{FD}, k_{SD} and k_{AD} as outlined in subclause A.4.2.2.1;

ii) compute the resultant correlation coefficient k as a product of all the partial correlation coefficients.

EXAMPLE:

For a combination of frequency and space separation:

$k^2 = k_{SD}^2 \cdot k_{FD}^2$

With the values of the previous examples (subclause A.4.2.2.1):

$k^2 = 0{,}852 \cdot 0{,}975 = 0{,}831$;

$D = (1 - k^2) = 0{,}169$.

A.4.2.2.3 Dual diversity arrangement

The basic law for dual diversity arrangements is [A4,A13-A15]:

$$P_{div}{}^2 = \frac{P^2}{\eta \cdot (1 - k^2)} \qquad (4\text{-}16)$$

The output is valid as far as it is less than P.

$P_{div} = P_{div}{}^2$ if $<P$

$= P$ elsewhere

EXAMPLE 1:

Reference path 50 km, f = 4 GHz, c = 1, h = 15 m, 140 Mbit/s, 16QAM:

- Unprotected channel:

  $P_0 = 0{,}3 \Rightarrow \eta = 0{,}078$;

  $d = 50\text{ km} \Rightarrow T_a = 0{,}7\text{ ns}$;

  $P_S = 2{,}65\times10^{-4}$;

  $M = 30\text{ dB} \Rightarrow P_F = 3{,}00\times10^{-4}$;

  $P = 5{,}65\times10^{-4}$.

- Channel with space diversity:

  $h = 15\text{ m}, f = 4\text{ GHz}, \Rightarrow k_{SD}^2 = 0{,}852 \Rightarrow (1-k_{SD}^2) = 0{,}148$

  $P_{div,2} = 2{,}8\times10^{-5} < 2{,}65\times10^{-4}$ therefore:

  $P_{div} = 2{,}8\times10^{-5}$;

  $I \approx P / P_{div} \approx 20{,}4$.

P_{div} traced versus P changes slope from 2 to 1 when P exceeds $m = \eta \cdot (1\text{-}k^2)$. The knee around this critical value is well described by the harmonic mean between asymptotes P_{div} and P:

$$P_{div} = \frac{1}{1\,/P_{div} + 1\,/P} = \frac{P}{I} \qquad (4\text{-}17)$$

where I = 1 + m / P

EXAMPLE 2:

With values of example 1:

$m = 0{,}0115 \quad \Rightarrow \; I = 1 + 20{,}4 \quad \Rightarrow \; P_{div} = 2{,}64\times10^{-5}$

The slope change of P_{div} versus P can be used to derive the m-value from experiments. Similarly the slope change of $P_{F,div}$ versus P_F and of $P_{S,div}$ versus P_S respectively defines coefficients m_F and m_S such that:

$P_{F,div} = P_F^2 / m_F$ and $P_{S,div} = P_S^2 / m_S$.

The output tends to case P_F when fade margin M is poor or average delay T_a is low, then $P_F >> P_S$. Vice versa the output tends to case P_S when margin M is large or T_a is high, then $P_S >> P_F$.

A.4.2.2.4 Split model

Generally applies:

$P_{div,2} = (P_S + P_F)^2 / m = P_F^2 / m_F + 2 \cdot P_F \cdot P_S / m_{FS} + P_S^2$

The expression on the right allows to use different m values for "flat fadings", "selective fadings" and their combination [A15]. A priori there are no strong reasons to do that, because of the same deep notch, passing through the signature and over the carrier frequency, produces both attenuation and intersymbol interference.

Anyway m_F and m_S can be detected by two different experiments; e.g. m_S from outage seconds in a system dominated by intersymbol interference and m_F from fading statistics.

EXAMPLE 1: (same values as example 1, but $k_S = 0$):

$\eta = 0{,}078$

$(1\text{-}k_F^2) = 0{,}148 \Rightarrow m_F = 0{,}0115$

$(1\text{-}k_S^2) = 1 \Rightarrow m_S = 0{,}078$

with $m_{SF} = \sqrt{m_S \cdot m_F} = 0{,}03$ we get

$P_{div,2} = 1{,}4\times10^{-5}$

Using conditional probabilities $P_{div}|MP$, plotted versus P, changes slope at $P = (1\text{-}k^2)$

$P_{div}|MP = P|MP^2 / (1\text{-}k^2)$ if $<P|MP$

$= P$ elsewhere.

Or in one equation:

$$P_{div}| MP = \frac{1}{1\,/(P_{div}| MP) + 1\;/(P\,|\,MP)} = \frac{P\,|\,MP}{I} \qquad \text{where}$$

$I = 1 + (1\text{-}k^2) / (P|MP)$

A.4.2.2.5 Quadruple diversity arrangements

Use the basic laws of subclause A.4.2.2 in a recursive way as already said.

Let for instance space and angle diversity be used, with:

channel 1: antenna height h1, beam tilt t1;

channel 2: antenna height h1, beam tilt t2; $\Delta\alpha$ = t2 - t1;

channel 3: antenna height h2, beam tilt t1 h = h2 - h1;

channel 4: antenna height h2, beam tilt t2.

i) **compute correlations and determinants of interest:**

k_{SD} = correlation due to space diversity alone;

k_{AD} = correlation due to angle diversity alone;

$k_{SD,AD}$ = $k_{SD} \cdot k_{AD}$ correlation due to combined effect of SD and AD;

$D(1,2,3,4) = (1-k_{SD}^2)^2 \cdot (1-k_{AD}^2)^2$;

$D(1,2,3) = D(1,2,4) = D(1,3,4) = D(2,3,4)$;

$= (1-k_{SD}^2) \cdot (1-k_{AD}^2)$;

$D(1,2) = D(3,4) = (1-k_{AD}^2)$ pure angle diversity;

$D(1,3) = D(2,4) = (1-k_{SD}^2)$ pure space diversity;

$D(1,4) = D(2,3) = (1-k_{SD,AD}^2)$ space & angle diversity.

ii) **compute all the following cases:**

$P_{div}|MP4 = P|MP^4 / D(1,2,3,4)$;

$P_{div}|MP3 = P|MP^3 / D(j,k,l)$, j,k,l all 4 combinations from above;

$P_{div}|MP2 = P|MP^2 / D(j,k)$ j,k all 6 combinations from above;

$P|MP = P/\eta$.

If channels 1 to 4 have different outage probabilities P1 to P4, then the product:

$P|MP_j \cdot P|MP_k$ must be used instead of $P|MP^2$, and the product $P|MP_j \cdot P|MP_k \cdot P|MP_l$ must be used instead of P/MP^3 and so on. In this case it is also necessary to examine all the cases of the same order, e.g. the 4 single channels, the 6 pairs and the 4 triples.

EXAMPLE:

Let be:

P = $5{,}65\times10^{-4}$;

η = 0,078;

$k_{SD}2$ = 0,852 ⇒ (1-$k_{SD}2$) = 0,148;

$k_{AD}2$ = 0,937 ⇒ (1-$k_{AD}2$) = 0,063;

$^{k}SD,AD^{2}$ = 0,798 ⇒ (1-kSD,AD^{2}) = 0,2;

D(1,2,3,4) = $8{,}7\times10^{-5}$;

D(1,2,3) = $9{,}3\times10^{-3}$;

D(1,4) = 0,2;

$P_{div}4|MP$ = $3{,}1\times10^{-5}$ ⇐ minimum output;

$P_{div}3|MP$ = $4{,}0\times10^{-5}$;

$P_{div}2|MP$ = $2{,}5\times10^{-4}$;

$P|MP$ = $7{,}2\times10^{-3}$;

$P_{div}|MP$ = minimum output = $3{,}1\times10^{-5}$;

P_{div} = $2{,}4\times10^{-6}$;

I = 235.

A.4.2.2.6 n+m system

Let m RF standby channels protect n RF service channels, carrying n main information streams I_1 to I_n. Additionally, m secondary information streams I_{n+1} to I_{n+m} can be carried by standby channels when they are not required to protect the main information streams.

Compute output probability P_i of the ith information stream as:

$$P_i = \sum_{j=0}^{R-1}(1-I_i)\cdot \Pr(event j) \tag{4-18}$$

where:

I_i = status of the ith information, 1 = OK, 0 = OUT during the jth event;

j = 0....$2^{(n+m)}$ - 1.

All the possible events can be listed in a table having R = $2^{(n+m)}$ rows.

The lowest row is j = 0 and the event is represented by (n+m) bits {C} = 0 to 0 = all channels OUT.

The highest row is j = $2^{(n+m)}$ - 1 and the event is represented by (n+m) bits {C} = 1 to 1 = all channels OK.

Service channels are protected according to their priorities.

EXAMPLE 1:

2+1 system. C_1 and C_2 are service channels, C_3 is the protection channel.

Q_1 and Q_2 are priority factors of the service channels, normalised to $Q_1+Q_2=1$.

Table A.1 2+1 system: Events and information status 1 = OK; 0 = OUT

EVENT j	STATUS OF CHANNEL			STATUS OF INFORMATION			EVENT PROBABILITY
	C_1	C_2	C_3	I_1	I_2	I_3	
7	1	1	1	1	1	1	1-(!)
6	1	1	0	1	1	0	P-(!!)
5	1	0	1	1	1	0	P
4	1	0	0	1	0	0	P^2/m(2,3)
3	0	1	1	1	1	0	P
2	0	1	0	0	1	0	P^2/m(1,3)
1	0	0	1	Q1	Q2	0	P^2/m(1,2)
0	0	0	0	0	0	0	P^3/m(1,2,3)

$Q2 = 1-Q1$; $m(i,j) = \eta \cdot D(i,j)$; $m(1,2,3) = \eta^{2\cdot} D(1,2,3)$;

(!) = Pr(event 0) +...+Pr(event 6) << 1;

(!!) = Pr(event 4) + Pr(event 2) + Pr(event 0) << P.

NOTE 1: Negligible terms as above not indicated in next rows.

NOTE 2: Only asymptotic law $P_{div} = P_{div,N}$ is quoted, where N = number of channel OUT.

EXAMPLE 2: (System of table A.1):

When standby channel is OK, $C_3=1$ while a service channel is OUT, e.g. $C_1=0$. In that case information I_1 will be carried by channel 3. Hence $I_1=1$, while information I_3, if present, will be lost, i.e. $I_3=0$. This case is identical with event j=3 in table 1.

When both service channels are OUT ($C_1=C_2=0$), while standby channel is OK ($C_3=1$), then information I_1 and I_2 will be saved, with probabilities Q_1 and $Q_2=1-Q_1$ proportional to their priority. Information I_3, if present, will be lost at any rate, i.e. $I_3=0$. This case is identical with event 1 in table A.1.

If m+x channels are OUT, then x information or service channels will be lost.

The probabilities of the events are computed using the basic law of diversity protection (used in recursive way as explained in the previous subclauses A.4.2.2.3 and A.4.2.2.4), and the theorem of the total probability.

EXAMPLE 3:

$Pr(C_1=0), C_3=0) =$	$Pr\ (C_1=0, C_2=0, C_3=0)\ + Pr$	$(C_1=0, C_2=1, C_3=0)$
compute with	compute with	value of interest
dual diversity	triple diversity	probability of
law used	law used	event j=2
recursively	recursively	in table A.1

EXAMPLE 4:

Assumptions:

$P_{div} = P_{div}^2 << P$

$(1\text{-}k_{FD}^2)$ proportional to frequency spacing Δf.

Channel	1	2	3
Frequency	f_0	$f_0 + \Delta f$	$f_0 + \Delta f$

Table A.2: Outage probability of a 2+1 system

PRIORITY		**OUTAGE PROBABILITY OF**		
Q_1	Q_2	I_1	I_2	I_3
0	1	1,5 P_{div}	1 P_{div}	3 P
½	½	1,0 P_{div}	1,5 P_{div}	3 P
1	0	0,5 P_{div}	2 P_{div}	3 P

A.4.3 Outage prediction: Approach 2

Approach 2 uses the methods of separating the flat and the selective part for each path of the diversity system. Then the concept of improvement factors is introduced for each part in the diversity system and the outage probability P_D is calculated.

The calculation of the outage probability according to approach 2 is based on the assumption that correlation behaviour for flat and for dispersive fading effects can well be different.

With this assumption it is expedient to use individual correlation coefficients K_F^2 and K_S^2 and corresponding improvement factors I_F and I_S for each of the fading effects in the calculation of P_D according to (4-4) or to (4-6). Thereby we obtain the following expressions for the outage probability with diversity operation:

$$P_{tot\ D} = \frac{P_F}{I_F} + \frac{P_S}{I_S} = P_{FD} + P_{SD}\ . \qquad (4\text{-}19)$$

Expression (4-19) is in keeping with our method of calculation for the unprotected single channel in (3-1), so that the remarks concerning the idealized partitioning of the degrading effects of multipath propagation in subclause A.3.1 are applicable here as well. It may be added that this approach facilitates economically oriented route planning: The dominating cause of outage can be recognised for each situation, enabling the application of specific countermeasures. For example, if $P_{FD} >> P_{SD}$ then the employment of better equalizers would hardly reduce the combined outage probability $P_{tot\ D}$. On the other hand, substantial improvement would be obtained by raising the transmitter power.

The proposed improvement factors will be explained in the following subclauses for the various diversity methods. It is assumed that the outage probabilities P_F given in (3-8) and P_S given in (3-12) for the single channel can be put in the form:

$$P_F = P_0 \cdot 10^{-FFM/10} \qquad (4\text{-}20)$$

and

$$P_S = \eta \cdot 10^{-SFM/10}\ . \qquad (4\text{-}21)$$

FFM is the effective resulting flat fade margin, which includes not only the influence of thermal noise but also the interference contributions. SFM is the selective fade margin which may be computed from (3-12).

A.4.3.1 Space diversity

A.4.3.1.1 Flat fade improvement factor

The improvement factor for flat fading can be calculated according to the Vigants formula [A5], [A6], [A7], which is one of the most suitable formulas for overland hops (even if the influence of the antenna separation seems to be overrated):

$$I_F = 1{,}2 \cdot 10^{-3} \cdot S^2 \cdot \left(f \,/\, d \right) \cdot 10^{FFM/10} \quad . \tag{4-22}$$

S is the vertical antenna separation in m, f is the operating radio frequency in GHz, and d is the route length in km.

A.4.3.1.2 Dispersive fade improvement factor

The available measurements on wide-band digital systems over hops for which outage is mainly due to dispersive fading show a distinctly different dependence of the improvement factor as predicted by (4-22):

While, on the one hand, the diversity effect for flat fading improves with greater antenna separation, the improvement factor I_S for dispersive fading reaches a maximum already at small separations and gradually falls back to a constant value as separation is further increased. This constant value depends on the severity of dispersive fading which, in turn, depends on the delay difference during multipath propagation, and therefore on the hop length d together with the sensitivity of the system to these distortions (signature). Constant values in the order of 50 to 100 have been measured for typical 140 Mbit/s systems with adaptive equalization for normal hop lengths. Empirical formulae with which the dependencies mentioned here could be estimated quantitatively have not yet been derived. We propose, therefore, to use the general formula (4-7) for the calculation of the improvement factor I_S for outages due to dispersive fading. On replacing the outage probability P in (4-7) by the expression for P_S in (4-21) we obtain:

$$I_S = \left(1 - K_S{}^2 \right) \cdot 10^{SFM/10} \quad . \tag{4-23}$$

The value for the expression $(1-K_S{}^2)$ in (4-23) is initially unknown. Our estimations - based on experimental results given in [A8] - indicate that its value lies between 1/20 and 1/10. Because these estimations are based on relatively few measurements and are thus comparatively uncertain, we suggest taking the lower (pessimistic) limit. The improvement factor is then given by:

$$I_S = \frac{1}{20} \cdot 10^{SFM/10} \quad . \tag{4-24}$$

A.4.3.2 Frequency diversity

A.4.3.2.1 Flat fade improvement factor

For frequency diversity with (1+1) protection, the application of the Barnett formula /9/ is recommended. According to this formula, the improvement factor is given by:

$$I_F = \frac{0{,}8}{fd} \cdot \frac{\Delta f}{f} \cdot 10^{FFM/10} \quad . \tag{4-25}$$

f, d and FFM have the same meaning as in (4-22), $\Delta f/f$ is the relative frequency spacing as a percentage.

A.4.3.2.2 Dispersive fade improvement factor

The dispersive fade improvement factor exhibits an equivalent behaviour with frequency diversity as with space diversity, see [A8], so the application of the same formula is recommended:

$$I_S = \frac{1}{20} \cdot 10^{SFM/10} \quad . \tag{4-26}$$

A.4.3.2.3 Reduction of improvement factors in case of (N+1) operation

The frequency diversity improvement factors I_F in (4-25) and I_S in (4-26) have to be reduced by a factor c, if only one protection channel is available for several (N) operating channels. To a good approximation, this factor is given by:

$$c = 1 + \frac{1}{2} \cdot \sum_{i=1}^{N-1} \frac{1}{i} . \qquad (4\text{-}27)$$

A.4.3.3 Combination of diversity methods

To maintain the required transmission quality even under unfavourable hop or propagation conditions it may sometimes be necessary to apply two (or more) diversity methods simultaneously, for example, space and frequency diversity. If K_1^2 and K_2^2 are the correlation coefficients of the two diversity methods, the combined correlation coefficient is the product of both:

$$K_C^2 = K_1^2 \cdot K_2^2 . \qquad (4\text{-}28)$$

The corresponding improvement factor as generally defined in (4-7) is therefore:

$$I_C = I_1 + I_2 - \frac{P}{\eta} \cdot I_1 \cdot I_2 . \qquad (4\text{-}29)$$

With reasonably low single channel outage probabilities P, the last term may be neglected, giving the simple formula:

$$I_C \approx I_1 + I_2 . \qquad (4\text{-}30)$$

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Annex B:
Description of the performance prediction model submitted by France

B.1 Introduction

The prediction method being developed by CNET/CRPE is intended to give, for a specified line-of-sight link, the outage time to be expected due to multipath selective fading.

The method is described in detail in [B1]. A more recent version is available in the 7th ICAP proceedings [B2].

In the present document, we describe the principles of the method in a simpler way, we present the implemented algorithm and we conclude with the present limitations of the methods as well as its expected improvements.

B.2 Principles of the method

In this method, the propagation channel and equipment characteristics are separated as far as possible.

B.2.1 The propagation model

The propagation channel is considered as a filter, the transfer function of which is described, on the frequency bandwidth of interest, by a three parameter mathematical model. For theoretical reasons, we have chosen, among several possibilities, the normalized two-ray model which has the following expression:

$$H(\Omega) = 1 - b \exp(-j(\Omega\tau+\Phi)) \qquad (1)$$

Ω being the angular frequency measured from the centre of the bandwidth of interest.

A particular path is then characterised by:

a) the probability P_0 of concurrence of multipath events;

b) the joint probability $Pr(b,\tau,\Phi)$ of equation (1) parameters when multipath events occur.

B.2.2 The statistical model

From data collected on several links, it appeared that the joint probability $Pr(b,\tau,\Phi)$ could be given the same mathematical description at any location, except for the numerical values of some coefficients. In this context, the three parameters of the normalized two-ray model can be described as statistically independent from each other, with:

- Φ following a uniform distribution on $[-\pi, +\pi]$;
- $|\tau|$ following a gamma distribution, with two coefficients μ and ν.

$$p(t) = \frac{\mu^{\nu}}{\Gamma(\nu)} e^{-\mu\tau} t^{\nu-1} \qquad (2)$$

The sign of τ depends on the minimum or non-minimum phase character of the transfer function b following a nearly uniform distribution on [0,1].

When taking the threshold condition into consideration, the b distribution is restricted to values greater than a value b_{min}, and the ϕ distribution is transformed into a symmetrical distribution with a single maximum near 0. These modifications are difficult to take into account analytically. Moreover, the b distribution is decreasing for b near to 1; although affecting only a small proportion of the transfer functions, this effect must be taken into account in order not to overestimate the outage time (b values near 1 correspond to very selective transfer functions).

B.2.3 The occurrence coefficient

More specifically, the occurrence of multipath events is defined as the occurrence of a selective fading having an attenuation greater than a threshold value S (in practice 5 or 10 dB) at any point of the frequency bandwidth. The probability P_0 of such an event can be related to the probability $P_f(S)$ of an attenuation greater than the threshold value at a given frequency. We thus have:

$$P_f(S) = r\,P_0 \tag{3}$$

The coefficient r is called the concurrence coefficient. It depends on the bandwidth, the threshold value and the intensity of the selectivity on the considered path (μ and ν coefficients of relation (2)). Once Pr(b,τ,Φ) is known, r can be obtained by a random simulation based on this distribution.

B.2.4 The outage domain

For a given criterion of outage (for instance a BER > 10^{-3}) it is possible to define the outage domain, a volume in the three dimensional (b,τ,Φ) parameters space. This domain is generally known and represented by a set of signature curves, which are its intersections with the constant τ-planes.

The outage domain depends on all the relevant parameters of the transmission equipment, including the flat fade margin. It can be defined, if appropriate, for the kind of equipment which incorporates corrective devices such as equalizers or other corrective filters.

Using the complete outage domain instead of a reduced signature (corresponding to neglecting thermal noise) leads to somewhat longer computations (a triple integral instead of a double one) but avoids any assumption concerning the (physically unrealistic) combination of separately computed flat and selective fading outages.

B.3 Description of the algorithm

B.3.1 Generalities

For specified path link and transmission equipment, the prediction algorithm has to provide the expected values of the occurrence probability P_0, the joint probability distribution Pr(b,τ,Φ) and from these the outage time:

$$T_0 = P_0 \int_D P_r(b,\tau,\Phi)\,db \cdot d\tau \cdot \cdot d\Phi \tag{4}$$

with D the outage domain.

Due to our presently partial knowledge, we make the following simplifying assumptions:

1) The probability distributions of b and Φ are independent from the link. The characteristics of the link therefore affect the selectivity of the channel only through the values of coefficients μ and ν of the τ distribution.

2) Among the many characteristics of the link, the hop length and the antenna aperture (or its equivalent diameter) are considered to have the predominant statistical effect on the selectivity of the channel. Coefficients μ and ν are related to these parameters by formulas:

$\mu(\phi f,D) = 1{,}7\times10^{4}\ (\phi f)^{-1{,}6}\ D^{-1}$ $\phi f < 22$and $D > 37$ km (5a)

$\mu(\phi f,D) = 1{,}6\ (\phi f)^{1{,}4}\ D^{-1}$ $\phi f > 22$and $D > 37$ km (5b)

$\mu(\phi f,D) = 12{,}4\ (\phi f)^{-1{,}6}\ D$ $\phi f < 22$and $D < 37$ km (5c)

$\mu(\phi f,D) = 1{,}17\times10^{-3}\ (\phi f)^{1{,}4}\ D$ $\phi f > 22$and $D < 37$ km (5d)

$\nu(\phi f) = 0{,}26\ (\phi f)^{0{,}6}$ (5d)

with D, the hop length in km, ϕ the antenna equivalent diameter in m, and f the frequency in Ghz.

3) The occurrence coefficient r can be obtained by simulation once μ and ν are known. It is tabulated only once for a sampling of μ and ν values. It does not vary too much and an approximate value of 0,9 can be used in any case.

4) The occurrence probability P_0 is then computed from the single frequency level distribution. We did not develop a new formula for this and the algorithm uses the single frequency level formula given by CCIR.

B.3.2 Algorithm

The algorithm is given in figure 1.

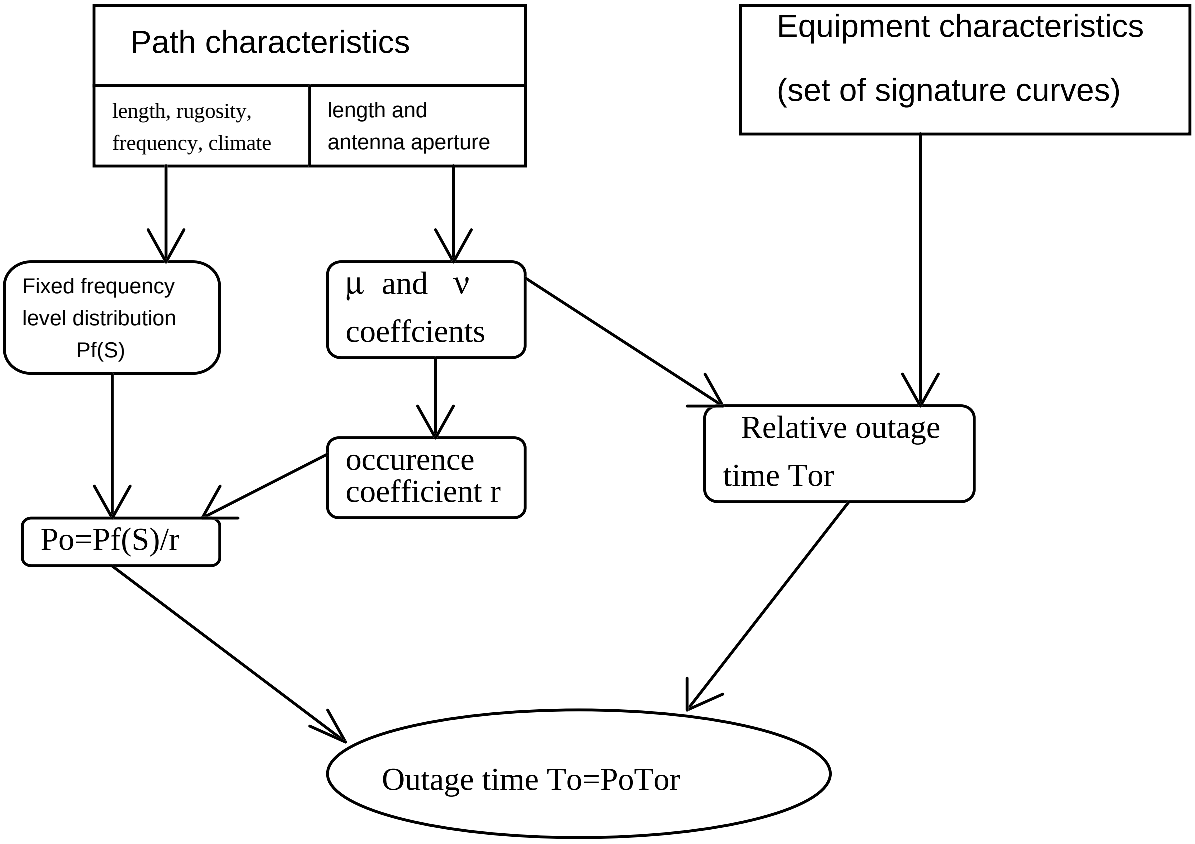

Figure 1

Let us make some comments on this figure. The fixed frequency level distribution Pf(S) is computed by the ITU-R method. Coefficients µ and ν are computed by formulas (5). The relative outage time T_{0r} given by:

$$T_{0r} = \int_D P_r(b,\tau,\Phi)db \cdot d\tau \cdot d\Phi \tag{6}$$

is computed by a Monte-Carlo method, using the previously determined values of coefficients µ and ν and the given set of signature curves. The occurrence coefficient r can also be computed form a random drawing from the Pr(b,τ,Φ) probability distribution. Using the value of 0,9 is likely to be sufficient, considering the accuracy of present prediction methods.

B.4 Limitations and expected improvements of the method

B.4.1 Limitations of the method

The method, in its present state, suffers from the following limitations:

1) It gives an expected value of the total outage time, but does not distribute it between availability and quality. At the time, our knowledge of the time variability of the propagation channel is not sufficient to allow us to do so.

2) The method is limited to multipath effects. Rain effects could be added using one of the satisfy existing prediction methods. A first approximation would consist in adding both effects. It is therefore not quite satisfactory (and probably pessimistic) because rain and multipath events have different seasonal variations.

3) The method does not consider co-channel and adjacent channel interferences. May be they could be taken into consideration by modifying adequately the flat fade margin.

4) The method in its present state is not adapted to diversity channel. The principles, however, for such an extension have been discussed in the paper given in document TM4 (89)/4.

B.4.2 Expected improvements of the method

In the coming two years, the method is expected to be improved in two ways:

1) By including a channel modelling adapted to space diversity.

2) By improving the assumptions made on the joint probability distribution Pr(b,τ,Φ).

B.5 References to annex B

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Annex C: Description of the performance prediction model submitted by Italy

C.1 Introduction

This document provides a detailed description of the performance and availability prediction method that is currently adopted by the Italian Administration. The method has been developed in CSELT and is delivered as a set of computer programs coded in FORTRAN language.

The model is fully described in references [C1] and [C2] for the non protected channel and space and frequency diversity and in [C3] for the angle and pattern diversity; a further paper for the latter subject is foreseen.

C.2 Input data

The input data required for the prediction method depend on the considered propagation effect (multipath, rain, etc.) and on the system configuration under study. The following list is comprehensive; in some cases only a subset of this list may be necessary:

a) path length (km);

b) frequency (GHz);

c) terrain roughness (m);

d) climatic zone (inland or coastal);

e) antenna: Gain (dB), Diameter (m), Focal length (m);

f) losses (dB): Radome, Waveguides and Branching;

g) transmitter power (dBm);

h) receiver: threshold for BER=10^{-3} (dBm), noise figure (dB) and bandwidth (MHz);

j) minimum and non-minimum phase signatures for BER=10^{-3};

k) carrier to Interference ratio (C/I) (dB);

l) diversity input data:

  - space diversity: Antenna spacing (m);
  - frequency diversity: Frequency spacing (GHz);
  - angle diversity: Separation between the two patterns (Degrees);
  - angle and pattern diversity: Separation between the two patterns (Deg) and secondary pattern data (see item no. 5);

m) average annual rainfall rate exceeded for 0,01 % of the time.

Items h and j are required also for BER=10^{-6}.

The computer program requires also several ancillary inputs in order to select the optional functions:

- Deep fade occurrence factor;
- Link margin;
- Envelope correlation coefficient;
- Minimum and non minimum phase contributions displayed separately.

C.3 Output data

The following output parameters are provided by the model:

- Probability of severely errored seconds (SES);
- Probability of errored seconds (ES);
- Probability of degraded minutes (DM);
- Probability of unavailability due to rain.

Several intermediate data (such as selective and non-selective contributions, multipath probability, etc.) are also provided.

C.4 Description of the method

The description of the method used is sub-divided into subclauses according to the particular system configuration under study and the considered propagation effect.

C.4.1 Non-protected channel (clear-air)

The prediction method is based on the simplified three ray multipath channel model:

$$H(f) = a \cdot \left[1 - k \cdot e^{2\pi(f - f_0)\tau}\right]$$

where a, k, f_0, τ are random variables (reference ray amplitude, echo relative amplitude, notch frequency offset and echo relative delay, respectively). The conditional outage probability, given frequency selective fading, may be written as:

$$P_{os/M} = F(k, f_0, \tau, S)$$

where S is a parameter dependent on the system (namely, the signature). The model, using a statistical description of the amplitudes of secondary rays (assumed to be Weibull distributed) and an exponential distribution for delays (whose parameters are related to the antenna radiation pattern), allows to take into account the contributions of both minimum and non-minimum phase fadings. The probability density function of echo delays is estimated from both path length d and antenna radiation pattern; the maximum echo delay $\tau_{\max}$ is given by the following relationship:

$$\tau_{\max} = (28{,}3 \cdot \Phi - 2{,}4) \cdot \left(\frac{d}{50}\right)^{1{,}5}$$

where Φ is half beamwidth at the level -5 dB.

The outage probability is obtained by integrating the joint density distribution function of the random variables defined by the channel model over the critical region in the probability space, responsible of outage events; after some manipulations and assuming that thermal contribution is negligible, the outage equation is:

$$P_{os/M} = \int_0^{\infty} p(\tau)\cdot d\tau \quad \int_{-\frac{1}{2\tau}}^{\frac{1}{2\tau}} \tau\cdot df_0 \quad \int_D p(k)\cdot dk$$

where D is the outage region defined by the minimum and non-minimum phase signatures.

The unconditional selective outage probability can be obtained by:

$$P_{os} = r\cdot P_{os/M}$$

where r is a scaling factor (selective fades occurrence probability during the worst month) that depends on propagation conditions and is related to the corresponding fading activity factor (or „deep fade factor") r' by means of:

$$r = r'\cdot e^{2\left(\mu-\sigma^2\right)}$$

where μ and σ^2 are the mean value and variance of the lognormal distribution of concurrent non-selective fades.

The non-selective outage probability, assuming high values of the flat fade margin L, is given by:

$$P_{ons} = r'\cdot 10^{-\frac{L}{10}}$$

The overall outage probability is finally obtained from:

$$P_0 = \left(P_{os}^{\frac{\alpha}{2}} + P_{ons}^{\frac{\alpha}{2}}\right)^{\frac{2}{\alpha}}$$

where the exponent α depends on the system and takes account of the fact that the selective and non-selective contributions do not affect the system separately; a reasonable value for most systems is α=1,5.

The main points that characterise this method are:

- minimum and non-minimum phase contributions can be computed separately and the relative weights as a function of the fade depth are evaluated;
- the probability density function of the multipath delays is estimated from the path length and the radiation pattern of the antenna.

The calculation of the flat fade margin L is performed by keeping into account both thermal noise N_t and interference I:

$$\frac{L^2\cdot C}{I+N_t} = (CNR)_{-3}$$

where C is the average signal power and $(CNR)_{-3}$ is the input signal-to-(noise + interference) ratio for BER=10^{-3}. Expressing the above quantities in decibel, the overall margin is obtained:

$$L = 10\cdot Log_{10}\left[10^{-\frac{L'}{10}} + 10^{-\left[\frac{C}{I}-(CNR)_{-3}\right]}\right]$$

where L' is the flat fade margin in the absence of interference.

C.4.2 Space and frequency diversity (clear-air)

As far as diversity is concerned the conditional selective outage probability is evaluated from:

$$P_{ods/M} = \int_0^\infty p(\tau)\cdot d\tau \int_{-\frac{1}{2\tau}}^{\frac{1}{2\tau}} \tau \cdot df_{01} \int_{-\frac{1}{2\tau}}^{\frac{1}{2\tau}} \tau \cdot df_{02} \int_D p(k_1,k_2)\cdot dk_1.dk_2$$

where the notch frequency offset of the two channels are assumed statistically independent and the two echo delays are assumed fully correlated.

The correlation coefficient r_w of the joint Weibull distribution of echo amplitudes k_1 and k_2 has been evaluated by comparing the resulting envelope distributions with the well known distributions obtained from two Rayleigh distributed signals with correlation coefficient r_v, as given by:

$$r_W = 1 - 0{,}0692\cdot(1-r_V)^{1{,}034}$$

The correlation coefficient r_v is also related to the non selective improvement factor I_{ns} by the following relationship:

$$I_{ns} = \frac{P_{ons}}{P_{odns}} = 1 + \frac{1-r_V}{P_{ons}}$$

where the non selective improvement is computed using the formulas proposed in ITU-R Report 338-6 [4].

C.4.3 Frequency diversity for N+u systems

The combinatorial calculus approach is utilised in the present method. The outage probability of an average working channel may be obtained using:

$$P_{av} = \frac{Z}{N}$$

with $Z = \sum_{i=1}^{N} \sum_{k=1}^{j\cdot(u+i)} (-1)^{i-1} \cdot \overset{u+i-2}{\underset{u-1}{C}} \cdot P_k(u+i)$

where N is the number of working channels, u is the number of protection channels, M=N+u is total number of channels, $P_k(u+i)$ is the simultaneous outage probability of the k^th possible combination of (u+i) channels and, finally, the following binomial coefficients are defined:

$$\overset{u+i-2}{\underset{u-1}{C}} = \begin{bmatrix} u+i-2 \\ u-1 \end{bmatrix} \quad ; \quad j(u+i) = \overset{M}{\underset{u+i}{C}} = \begin{bmatrix} M \\ u+i \end{bmatrix}.$$

In the less general (but often used) case of N+1 protection (u=1) the complexity of the above expressions is greatly reduced.

As far as the outage probabilities $P_k(u+i)$ are concerned, the present method allows the computation of the terms $P_k(2)$, whereas the contributions of the simultaneous outage probabilities on more than 2 channels are neglected.

C.4.4 Angle diversity

The amplitudes of the received signals r_1 and r_2 are obtained from the following relationships:

$$r_1 = 1 + k_1 \cdot e^{-j\varphi}$$
$$r_2 = f \cdot g_2(\delta) \cdot \left(1 + k_2 \cdot e^{-j\varphi}\right)$$

where the relative amplitudes k_1 and k_2 are defined by:

$$k_1 = k \cdot g_1(\theta)$$
$$k_2 = k \frac{g_2(\theta - \delta)}{g_2(\theta)}$$

and g_1 and g_2 are the antenna radiation patterns, δ is the angular separation between the two patterns, $f = G_2/G_1$ is the ratio between the maximum gains of the two antennas and k, θ and Φ are the amplitude, the angle of arrival and phase of the secondary ray with respect to the reference ray.

Two main assumptions are made in the above model:

- only two rays are received;
- the reference ray is supposed to be boresight with respect to antenna pattern $g_{1.}$

As far as the non selective outage probability $P_{odns/M}$ is concerned, the following condition must be satisfied:

$P_{odns/M}$=probability that (e_1<L) and (e_2<L),

where e_1 and e_2 are the envelopes received at the two channels and L is the common fade margin.

The above probability is obtained from the evaluation of the following integral:

$$P_{odns/M} = \int_{\varphi_1}^{\varphi_2} \frac{1}{2\pi} \int_{k_{1i}(\varphi)}^{k_{1s}(\varphi)} dk_1 \int_{k_{2i}(\varphi)}^{k_{2s}(\varphi)} p(k_1, k_2) dk_2 \,,$$

where the integration limits define for each channel the locus of the points where the envelope of the received signal is below the threshold L; $p(k_1,k_2)$ is the bi-variate distribution of the relative amplitudes.

If complete correlation between notch frequency offsets and echo delays is now assumed, the selective outage probability is given by:

$$P_{ods/M} = \int_0^\infty p(\tau) \cdot d\tau \int_{-\frac{1}{2\tau}}^{\frac{1}{2\tau}} \tau \cdot df_0 \int_D p(k_1, k_2) \cdot dk_1 \cdot dk_2 \,,$$

where the critical region D is determined by the signatures of the system.

The joint probability density $p(k_1,k_2)$ can be evaluated by means of the following transformation from the random variables (k,θ) to (k_1,k_2):

$$p(k_1, k_2) = p(k, \theta) \cdot \left| J\left[\frac{k, \theta}{k_1, k_2}\right] \right|$$

where J(·) is the Jacobian of the transformation and p(k,θ) is the joint statistics between the angle of arrival and the relative amplitude of the secondary ray.

Assuming that the variables k and θ are completely un-correlated, the joint probability is computed from:

$$p(k,\theta) = p(k) \cdot p(\theta),$$

where p(k) is the usual Weibull distribution and p(θ) is now assumed to be gaussian with parameters depending on the link characteristics. The further assumption of gaussian shaped radiation patterns allows the derivation of an analytical expression for the Jacobian.

C.4.5 Rain attenuation

The assessment of the system unavailability due to rain is computed using either the framework of the ITU-R method (ITU-R Report 338-6 [4]) or a method developed in CSELT, based on the synthetic storm approach [C6], [C7]. The main advantage of the former is that only the rain rate $R_{0,01}$ exceeded for 0,01 % of the time is needed as a climatological input. This datum can easily be obtained either from meteorological measurements or from ITU-R radiometeorological data bank. On the other hand, the latter method requires an input data set (such as rainfall recordings, wind velocity statistics, etc.) that is not always easily available. Nevertheless, due to its physical nature, the synthetic storm approach has been proved to be a satisfactory tool for the assessment of not only rain induced attenuation but also of other radio-electric parameters, such as cross-polarization [C7].

C.5 Analysis of the method

The method described in clause C.4 is now analysed, as far as clear-air propagation is concerned, in order to emphasize its trends as a function of certain input parameters.

C.5.1 Non protected and diversity channel

The outage probability is analysed as a function of a set of input parameters chosen in order to describe its dependence on physical quantities directly related to the phenomenon under study; in particular the fade margin, the delay dispersion and the signature have been considered.

The following input parameters have been adopted:

- Frequency: 7GHz;
- Path length: 50 km;
- Terrain roughness: 25 m (inland);
- Antenna:
  - gain: 40 dB;
  - diameter: 4 m;
  - f/d 0,35;
- Losses: 4 dB;
- Transmitter:
  - power: 27 dBm;
  - threshold: -70 dBm;
- Signature at 6,3 ns: rectangular (26 dB, 20 MHz);
- Space diversity: 5 m.

The dependence of the total outage probability on margin is reported in figure C.1 for both the non protected and diversity channel. The following considerations may be drawn:

a) The outage limit value for high system margin is equal to the selective probability.

b) For small values of the margin the slopes of the curves are equal to 10 dB/decade and 5dB/decade for the single and the diversity channel, respectively.

As far as the dependence of the outage on the delay dispersion is concerned, figures C.2 and C.3 provide the plots of total and selective probabilities versus the average delay.

The main points arising from an analysis of the figures are:

a) The probabilities tend to be constant for small delay dispersion; this value is equal to the non selective contribution.

b) The limits for high values of dispersion are equal to the multipath probability if total outage is considered and to unity if the conditional selective component is considered.

c) If the delay dispersion is ≤ 10 ns, the conditional selective outage probability for the non protected channel is proportional to the square of the average delay, whereas for the diversity case a fourth power law is observed.

The sensitivity of the outage probability with respect to the system signature is analysed making use of the parameter W/T' where W is the signature width [MHz] and T' is defined as:

$$T' = \frac{\tau_r}{10^{-\frac{B_c}{20}}}$$

where B_c is the signature depth measured at a reference delay τ_r. Figure C.4 reports the results of this analysis; the following points may be noted:

a) The non protected channel outage is proportional to the signature parameter W/T'.

b) The diversity probability is proportional to the square of signature parameter.

The following conclusions can now be drawn:

a) The diversity outage probability $P_{od/M}$ conditioned to multipath is related to the single channel value $P_{o/M}$ by the following relation:

$$P_{od/M} = \frac{P_{o/M}^2}{m}$$

where the parameter m depends on the correlation coefficient between the two signals.

b) The conditional outage selective probability $P_{os/M}$ for the non protected channel can be expressed by the following relationship:

$$P_{os/M} = C \cdot \frac{W}{T'} \cdot \tau_m^2$$

where τ_m is the average delay [ns] and the constant C, evaluated from a regression analysis, was found to be equal to about 8.

It should finally be noted that the analysis outlined above is consistent with the concepts expressed in ITU-R Report 784 in the section concerning outage computation using signatures.

C.5.2 Angle diversity

The present subclause provides an overview of the capabilities of the angle diversity model described in clause C.4. The test link taken into account has the following characteristics:

- Frequency: 7 GHz;
- Path length: 40, 50 and 60 km;
- Terrain roughness: 26 m (inland);
- Antenna:
  - gain: 43,6 dB;
  - diameter: 3 m;
  - f/d: 0,35;
- Losses: 4 dB;
- Transmitter power: 27 dBm;
- Receiver threshold: -70 dBm;
- Signature width: ±16 MHz;
- depth: 14 dB;
- reference delay: 6,3 ns.

NOTE 1: Calculations have been performed for three different link lengths and for radiation patterns separations ranging from 0,01°C to 1,0°; results have been plotted in figure C.5 where the selective and the non-selective contributions have been separated.

NOTE 2: The analysis of the figure points out the following major considerations:

a) The diversity improvement reach its maximum value for an angular separation close to the antenna -3dB beamwidth, irrespective of path length.

b) The selective improvement **decreases** as the path length increases; **the opposite trend** is observed for the non-selective contribution.

C.6 Conclusions

An outline of the radio link performance prediction method, currently adopted by the Italian administration for planning purposes, is presented. The detailed description and the analysis performed have been provided, as requested by TM4 specifications, in order to clarify, together with the previous documents [C1] - [C7], the capabilities of the model. The applications that are covered by the method range from different equipment types, interference effects, path characteristics to various possible countermeasures against radio-link degradations. The framework of the model makes use, whenever possible, of general physical concepts that allow further extensions according to new achievements of the related studies.

C.7 References to annex C

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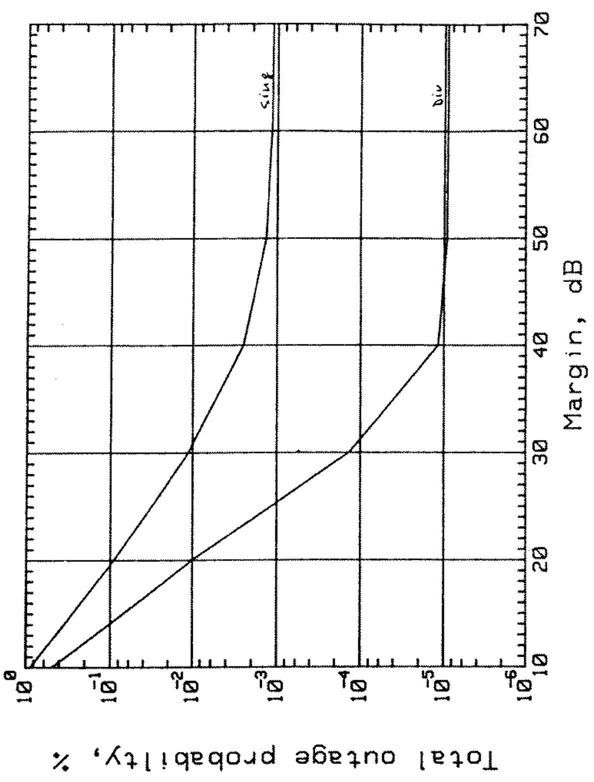

Figure C.1: Outage versus Margin for the clear-air propagation model

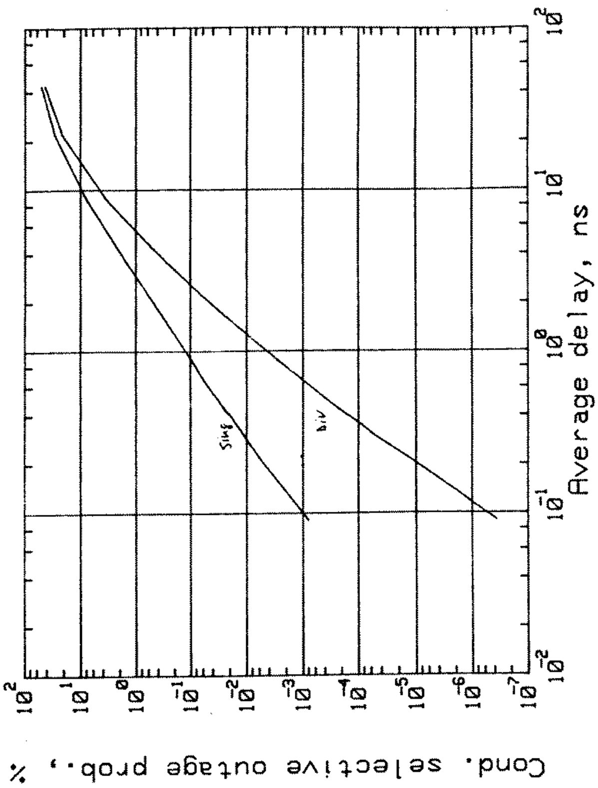

Figure C.3: Conditional selective outage probability versus average delay

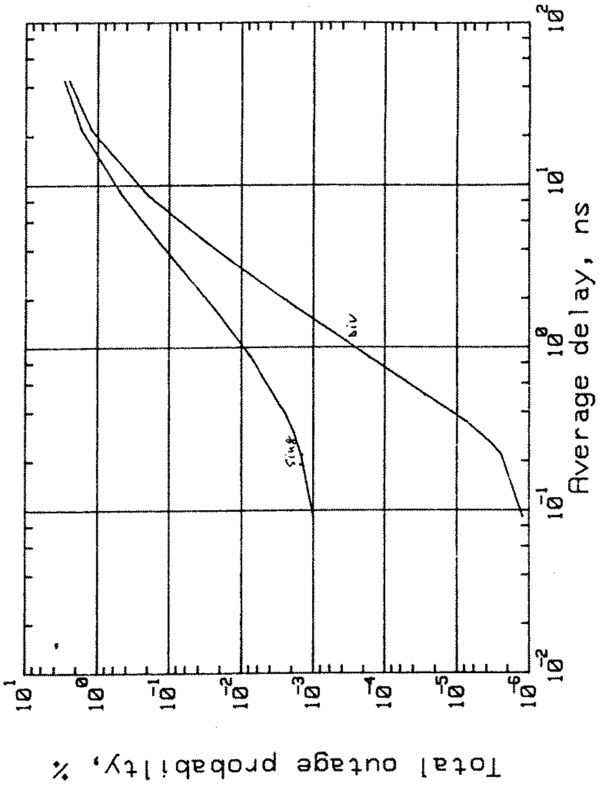

Figure C.2: Total outage versus average delay for the clear-air propagation model

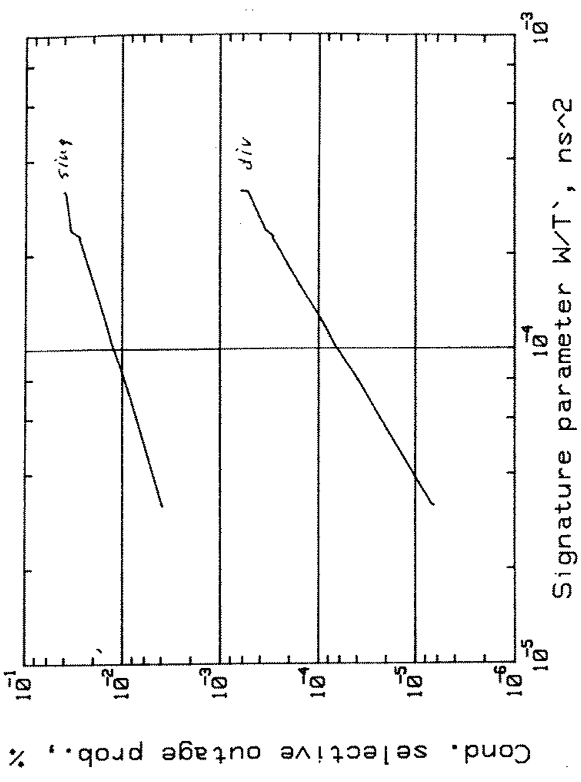

Figure C.4: Conditional selective outage probability versus the signature parameter

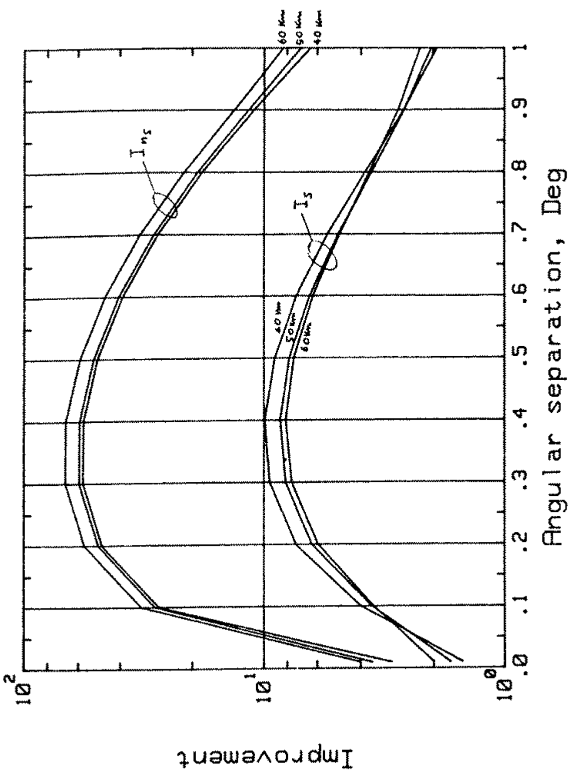

Figure C.5: Selective and non selective improvements versus the angular separation. The parameters the hop length

Annex D: Description of the performance prediction model submitted by UK/GPT: "The GPT Radio Performance Prediction Model" (Peter W. Hawkins -GPT Network Planning)

D.1 Overview of computer aided planning capability

GPT has developed a suite of computer programs to enable the prediction of severely errored seconds, degraded minutes, errored seconds and availability during microwave route planning and engineering. This program suite has been in commercial use by GPT for many years.

The ITU-R performance and availability recommendations based on Reports 634, 1052, 1053 and 557 are used to derive target allocations for use within the programs - with flexibility to adjust the allocations on a hop or route basis depending on the network reference circuit and customer requirements. The GPT model is used to predict the probability of unavailability and the probability of degraded performance due to flat and selective fading; countermeasure enhancements are included in the predictions.

Fade dependent and fade independent interference (and noise) arising from sources within and outside the route being engineered can also be accommodated. Interference can arise from direct transmit/receive interaction through RF multiplex and from feeder echoes, adjacent hops, over reach, co-frequency cross-polar channels, and adjacent co- and cross-polar channels; additionally, in cross-polar cases the XPD degradation during multipath and rain must also be considered.

Switched frequency and space diversity systems as well as continuously combined space diversity configurations are modelled. A careful determination of the most appropriate switching thresholds, both in the forward and reverse directions, is necessary when assessing the improvement factors presented by switched countermeasure techniques.

GPT's core prediction model for assessing performance under selective fading uses ITU-R fading data drawn from ITU-R Report 338-6 [4] where the so called "multipath fading occurrence factor" (embracing fading activity and a distribution variance) is seen as dependent on climatic/topographical and roughness factors as well as transmission frequency and distance.

The dependence of outage on equipment signatures is well known and signatures are normally assessed as simple masks in the minimum and non-minimum phase domains. However, for more complex signatures an integration approach can be used.

Modelling is based on the Rummler simplified three ray format which can be considered as embracing selective and non-selective fade elements. Two techniques have been identified for assessing and combining the effects of flat and selective fading:

a) a simple method employing either linear or non linear combining algorithms can be chosen using the ITU-R fading equation given in ITU-R Report 338-6 [4] plus GPT's selective fading model with non stressed signatures; or

b) a more complex method (under development) which integrates over the normal and the expanded or stressed signatures that result from noise/interference entering the system.

Degraded minute estimations include an appropriate factor to address the one minute integration time, and errored seconds are translated from system baud rate to the 64 kbit/s level based on a ITU-R method. Rain attenuation will affect degraded minute time and is assessed depending on rain rate and its seasonal relationship to multipath throughout the world. Beam elevation information is obtained from antenna-tower height/terrain profile plot programmes.

Where relevant, ITU-R prediction methods are used as a base for engineering and model building. As stated above, the fading occurrence factor drawn from ITU-R Report 338-6 [4] is used as a base to derive the probability of degraded performance whereas the effects of rainfall are determined directly from Reports 338, 563 and 721, leading to average annual probability of unavailability and the worst month probability. The reduction in cross-polar discrimination that occurs during multipath and during rainfall is assessed using the formulae in ITU-R Report 338-6 [4] as a guide.

D.2 Prediction model

This subclause briefly describes the development of GPT's model for predicting degraded performance and details the techniques used to assess severely errored seconds, degraded minutes and errored seconds, together with a discussion of system interference and its effects on system budgets.

D.2.1 Selective fade predictions

The development of degraded performance assessment techniques for medium and high capacity digital systems is based on the Rummler "simplified three ray model" - also described as a two ray model with flat attenuation [D1, D2].

The transfer function for this model is:

$$H\omega = a\left(1 - b \cdot e^{\pm\left(\omega - \omega_m\right)T}\right) \tag{1}$$

Townsend reports that the model correctly describes measured transfer functions for bandwidths up to 55 MHz [D3] when T is fixed at 1/(6B), where B is the bandwidth. There are then three variable parameters, namely a, b, and ω. The parameter a represents an overall attenuation, b the echo amplitude component and ω the frequency, with ω_m the centre frequency.

It is generally accepted that this model adequately represents the majority of multipath fading events: Sasaki and Akiama [D4] indicate that even a two ray model satisfactorily describes a limited bandwidth channel for up to 90 % of time.

Further, it is generally agreed that the overall fading probability can be described by distributions which show Rayleigh characteristics (Pr) during periods of multipath activity (activity time n during worst months) and Gaussian/log-normal characteristics (Pg) during periods of non-multipath activity. Hence the overall probability can be described by:

$$n \cdot Pr + \left(1 - n\right) \cdot Pg \ . \tag{2}$$

These distributions embrace the usual variance and mean parameters. When deeper fading is considered, the Rayleigh fade dominates and the probability of fading can be approximated to $n \cdot Pr$.

On narrowband radio systems the probability of a fade being greater than a given fade margin FM can be expressed simply as:

$$P\left(F > FM\right) = Po \cdot 10^{-FM/10} \ , \tag{3}$$

where Po is referred to as the "multipath occurrence factor" [D5].

However, the performance of wideband digital systems is subject to flat and selective fading elements as represented by Rummler's model, - the selective elements causing amplitude and phase dispersion in the channel.

Predicting the probability of degraded performance due to selective multipath fading necessitates an assessment of the complex outage space embraced by a joint probability distribution of the relevant variable parameters. Methods employing complex integrals of the following type could be used:

$$P\left(D(s)\right) = \underset{outage\ space}{\iiiint} P\left(a, b, \omega, T\right) da\ db\ d\omega\ dT \ , \tag{4}$$

where P (a, b, ω, T) represents the joint probability distribution.

GPT decided to investigate a model that would faithfully represent the facts and could be quickly and reliably used during radio systems planning. If at all possible the probability of degraded performance due to selective fading P(D(s)) would be described by a function embracing relevant parameters and be of the form:

$$P(D(s)) = Po \cdot f(a, b, \omega, T, E) \qquad (5)$$

to replace the complex integral noted above. In this equation:

- Po - represents the fading occurrence factor;
- a - the depressional fading component;
- b - the echo amplitude;
- T - the echo delay;
- ω - the notch frequency;
- and E - other possible equipment/system factors.

The development proved to be possible and an effective model was developed and refined.

The occurrence factor Po used in the model has been researched and documented by many workers and was accepted as suitably practical for inclusion in the GPT model. However research into "activity and occurrence" continues and could entail some modification to factor Po.

An expression for Po is obtained from equation (3) of ITU-R Report 338-6 [4], where:

$$Po = K \cdot Q \cdot F^{B} \cdot D^{C} , \qquad (6)$$

with KQ - factor embracing climate and topographical conditions (including roughness), see table 1 of ITU-R Report 338-6 [4];

- F = frequency (GHz);
- D = path length (km);
- B and C are factors drawn from table 1 in of ITU-R Report 338-6 [4].

Other relevant references to the occurrence factor (combining a multipath activity factor, n, and the Rayleigh variance) can be found in work by Serizawa and Takeshiti [D6] and Mojoli [D5,D7]; Mojoli also introduced a parameter to represent path roughness.

Equipment signatures (describing equipment sensitivity to echo signals) are used within the model as a convenient method of representing multipath outage domains.

They are measured using simulated two ray multipath in the minimum and non-minimum phase format under conditions of normal receive level and reduced received level. Signatures measured at reduced signal levels are referred to as stressed signatures.

An integration/summation over the outage space in the non-minimum and minimum phase domains is used to assess the effects of the equipment signature on degraded performance: (this integration allows "convoluted" and "island" signatures to be readily assessed). The integral is:

$$\int\int_{outage\ space} Bm(T,\omega,a) \cdot Bnm(T,\omega,a)\ dT\ d\omega\ \ da \ , \qquad (7)$$

where Bm and Bnm are minimum and non-minimum signature heights respectively with T representing the average path delay.

The occurrence probability of minimum and non-minimum phase fading is adjusted in relation to geographic and distance parameters.

In practice, signatures (measured at a delay To) are scaled to reflect the average path delay to be expected. Ruthroff [D8] deduced that:

$$T(\max) \propto D^3 \quad (8)$$

although Mojoli [D9] suggested that the third power distance exponent was too pessimistic and that a 1,5 exponent was more appropriate. In developing the GPT model it was found that an exponent around 1,3 to 2,0 provided the best fit with measured data.

The equipment signature curves can be scaled over limited ranges, and signature heights and widths are adjusted against the delay To to reflect the average path delays expected. Height is scaled directly by using the average path delay whilst width scaling is reduced using a decimal exponent.

As stressed signatures are not usually specified by equipment manufacturers and are not being addressed as part of the ETSI harmonisation/certification processes, the effects of selective and flat fading will be separately assessed. For continuity these will be referred to as P(D(s)) and P(D(f)).

P(D(s)) can now be described by the dependence:

$$Po \cdot f\left(Bm, Bnm, T, To, \omega, E\right) \ . \quad (9)$$

For "rectangular" signatures this probability equates to:

$$Cons\tan t \cdot Po \cdot \left(\text{sign. width}\right) \cdot \left(\text{sign. height}\right) \cdot \left(T / To\right)^{1,1} \cdot E^{X} \ , \quad (10)$$

where E represents the system bit rate.

As alluded to above, two approaches to performance predictions are possible:

a) The stressed signature analysis.

b) The combination of separate flat and selective probabilities.

This document, for reasons stated, confines itself to the second approach where the two probabilities can be simply summed or more realistically combined on a power basis where:

$$P\left[D(f) + D(s)\right] = \sqrt[Y]{P\left(D(f)\right)^{Y} + P\left(D(s)\right)^{Y}} \ . \quad (11)$$

The "flat" fade component P(D(f)) occurring during anomalous activity can be estimated using formula (3) from ITU-R Report 338 [4], where for the average worst month the probability of fading below a power level W is given as:

$$P\left(F > W\right) = K \cdot Q \cdot F^{B} \cdot D^{C} \cdot W / Wo \quad (12a)$$

or

$$P\left(F > W\right) = Po \cdot 10^{-FM/10} \ , \quad (12b)$$

where:

- W - received power (watts);
- Wo - non faded received power (watts);
- FM - system flat fade margin to depth W (dB); and
- Po - as previously given;
- predictions of severely errored seconds and degraded minutes at the system baud rate are tentatively assumed to apply at the 64 kbit/s level: a factor is used to translate to the one minute integration time when assessing degraded minutes;

- as error distributions due to anomalous propagation are continually being investigated (with conflicting reports), errored seconds are treated according to ITU-R Study Group Interim document 9/227-E (June 85) using the piecewise linear approach to move from system to 64 kbit/s level;
- the model has been extended to predict the effects of antenna beamwidth on performance and to include an assessment of cross-band diversity improvement factors;
- the effects of antenna beamwidth are modelled by assessing the echo angle of arrival and translating the antenna discrimination at this angle through to an improved signature height which is then used in performance predictions;
- improvements associated with cross-band diversity are computed similarly to in-band frequency diversity using the net fade margin concept.

D.2.2 Rainfall effects on performance and unavailability

The effects of rainfall on the unavailability of a radio relay system together with the effects on degraded minutes and errored seconds, are estimated from ITU-R Report 338 [4] - equation (18): (unavailability is defined in ITU-T Recommendation G.821 [1]).

$$Ap / A(0{,}01) = 0{,}12 \times p^{-(0{,}546 + 0{,}043 \log p)} \qquad (13)$$

where:

- p - represents % time;
- Ap - attenuation exceeded for time p % (dB);

and:

$A_{(0,01)}$ =(specific path attenuation) x L x r (dB); (14)

with:

- L - path length (km);

and:

r (path reduction factor) = 1/(1+0,045L). (15)

Specific path attenuation (dB/km) can be deduced from ITU-R Report 721:

where:

attenuation = $K \cdot R^{\alpha}$ (16)

with rain rate R derived from Report 563 and the coefficient K and α from equations (2) and (3) plus table 1 of ITU-R Report 721.

ITU-R Reports 634, 1052, 1053 and 557 must be carefully analysed when assessing performance and unavailability, as rainfall causes attenuation and hence errors when the radio system is still available.

The word wide seasonal variations and the coincidence between multipath effects and rainfall must be considered when estimating degraded minutes and errored seconds: to this end a relationship between average annual probability p and worst month probability pw from ITU-R Report 338 [4] equation (19) is necessary, i.e.:

$$p = 0{,}3 \times pw^{1{,}15}\% \qquad (17)$$

As well as the system unavailability due to rainfall, the overall system availability will of course depend on the reliability of equipment expressed as the "mean time between failures" (MTBF) plus the "mean time to restore" (MTTR) the equipment to a working condition after a failure, where

Availability = MTBF/(MTBF+MTTR) (18)

D.2.3 Space and frequency diversity

If the level of fading correlation between diversity channels is expressed by a factor C then the probability that the two channels experience fading to a given level can be defined by:

$$\mathrm{P}\big(\mathrm{F}(\mathrm{ch}\ 1)\big)\cdot\mathrm{P}\big(\mathrm{F}(\mathrm{ch}\ 2)\big)/(1-\mathrm{C})\ . \qquad (19)$$

As detailed in the subclauses above, critical outage space analysis can be used to assess degraded performance and can easily be adapted to diversity reception. However the ITU-R improvement factor concept can usefully be adopted for generalised prediction work where the probability that two individual channels will experience a specified BER simultaneously can be expressed as:

$$\mathrm{P}(\mathrm{div})=\mathrm{P}(\mathrm{ind})/\mathrm{I}\ , \qquad (20)$$

where I is an improvement factor.

In the space diversity case, a basic improvement factor I is derived from equation (10) of ITU-R Report 338-6 [4].

$$\mathrm{I}=1{,}2\cdot10^{-3}\cdot\mathrm{S}^{2}\cdot(\mathrm{F}/\mathrm{D})\cdot10^{(\mathrm{EFM}-\mathrm{G})/10}\ , \qquad (21)$$

where:

S = vertical separation of antennas (m);

G = gain difference between antennas (dB); and

EFM = effective fade margin.

For path lengths over 75 km, equation (12) can be used.

For frequency diversity, equation (13) is used to provide the improvement factor:

$$I=0{,}8/(F\times D)\times(\mathrm{D}F/F)\times10^{EFM/10}\ , \qquad (22)$$

where:

- Δ F - RF channel spacing (GHz).

Multiline (n+1) switching systems are modelled using a reduced or effective channel spacing based on:

$$\Delta\mathrm{F}=\mathrm{n}/\sum\mathrm{k}\big(1/\Delta\mathrm{F}(\mathrm{k})\big)\ , \qquad (23)$$

where k is the summation over all channel pair difference frequencies Δ F [D10].

The effective fade margin is derived from the overall probability of degraded performance P(D) (as determined from the techniques outlined previously) using the equation:

$$\mathrm{P(D)}=\mathrm{Po}\cdot10^{-\mathrm{EFM}/10} \qquad (24)$$

It should be noted that many forms of continuously combined and switched diversity configurations are feasible necessitating modifications to the improvement factor depending on the performance parameter being assessed. An example of this requirement is easily seen by considering the improvement thresholds in relation to switching thresholds (forward and reverse switching) when predicting degraded minutes and errored seconds. A system might switch to a standby channel at BER=10^{-4} and might return from standby when the main channel has improved to BER=10^{-6}.

The definitions of the three performance parameters as given in ITU-T Recommendation G.821 [1] should be strictly adhered to when assessing degraded performance.

D.2.4 The effects of interference

The stressed signature method - used to predict the effects of additive noise and interference on a system - is considered to reflect the "more correct" interference modelling approach. A simpler method - that is consistent with combining flat and selective fade probabilities modifies the system flat fade margin by revising the basic noise floor, and modifies the threshold carrier to noise ratios of the receiver in relation to fade independent and fade dependent interference respectively.

The total basic noise of the receiver is calculated from the power summation of K·T·B·F and fade independent interference:

$$\sum\left(\mathrm{N}, \mathrm{TRI}, \mathrm{ACI}, \mathrm{AFBI}, \ldots \mathrm{etc}\right) = 10 \cdot \lg\left(10^{0{,}1 \cdot \mathrm{N}} + 10^{0{,}1 \cdot \mathrm{TRI}} + 10^{0{,}1 \cdot \mathrm{ACI}} + 10^{0{,}1 \cdot \mathrm{AFBI}} + \ldots \mathrm{etc}\right) \mathrm{dBW} \tag{25}$$

where:

- N - K·T·B·F (dBW);
- TRI - transmit / receive interference (dBW);
- ACI - adjacent (and co-) channel interference (dBW);
- AFBI - interference through F/B ratio of antenna (adj. hop) (dBW);
- etc.

The basic receiver carrier to noise ratio (C/N) (which includes equipment imperfections) is modified by combining the following fade independent carrier to interference ratios (i.e. fade dependent interference):

- C/AFBI - carrier to interference through F/B ratio of antenna (same hop);
- C/EI - carrier to echo interference;
- C/ACI - carrier to adjacent (and co-) channel interference.

The overall carrier to noise ratio is determined from

$$-10 \cdot \lg\left(10^{-0{,}1 \cdot \mathrm{C/N}} - 10^{-0{,}1 \cdot \mathrm{C/AFBI}} - 10^{-0{,}1 \cdot \mathrm{C/EI}} - 10^{-0{,}1 \cdot \mathrm{C/ACI}} \ldots \mathrm{etc}\right) . \tag{26}$$

Interference from over reach, other routes, other systems, plus spurious and image interference, can be embraced in the models as required.

Cross Polar Discrimination (XPD) and equipment Interference Rejection Factors (IRF's) determine the amount of interference from adjacent and co-frequency channels on the same radio route.

ITU-R Equation (24):

XPD = -CPA + XPDo + Q (clear air) (27)

and equation (25):

XPD = U - V(F) lg (CPA) (Precipitation) (28)

from ITU-R Report 338-6 [4] are used as a guide when assessing levels of cross-polar interference. Other useful data is presented in ITU-R Report 722.

D.3 Summary of equations

1) For adjacent channel interference assessments:

$$\mathrm{XPD} = -\mathrm{CPA} + \mathrm{XPDo} + \mathrm{Q}$$

from ITU-R Report 338-6 [4] equation (24).

$$\text{Modified noise floor} = 10 \cdot \lg\left(10^{0,1 \cdot \mathrm{KTBF}} + 10^{0,1 \cdot \mathrm{ACI}}\right) \mathrm{dBW}\ .$$

2) For multipath fades:

$$\textit{probability of degraded performance} = \sqrt[Y]{P(D(f))^{Y} + P(D(s))^{Y}}\ ,$$

where:

$$\mathrm{P(D(f))} = \mathrm{Po} \cdot 10^{-\mathrm{FM}/10}\ ,$$

$$\mathrm{Po} = \mathrm{K} \cdot \mathrm{Q} \cdot \mathrm{F}^{\mathrm{B}} \cdot \mathrm{D}^{\mathrm{C}}$$; from ITU-R Report 338-6 [4], equation (3)

and:

$$P(D(s)) = 124\,000 \cdot Po \cdot (T / To)^{1,1} \cdot (\textit{signal width}) \cdot (\textit{signal height}) \cdot E^{X}\ ,$$

$$\mathrm{T} = 0{,}036 \cdot \mathrm{D}^{\mathrm{Z}}$$

3) For diversity operation:

Equations (10) and (13) from ITU-R Report 338-6 [4]:

$$\text{Space diversity improvement} = 1{,}2 \cdot 10^{-3} \cdot \mathrm{S}^{2} \cdot (\mathrm{F}/\mathrm{D}) \cdot 10^{(\mathrm{EFM}-\mathrm{G})/10}\ ;$$

$$\text{In} - \text{band frequency diversity improvement} = [0{,}8/(\mathrm{F} \cdot \mathrm{D})] \cdot (\mathrm{dF}/\mathrm{F}) \cdot 10^{\mathrm{EFM}/10};$$

where:

$$EFM = -10 \cdot \lg\left[(\textit{probability of degraded performance}) / Po\right]$$

D.4 Conclusion

Performance prediction techniques based on a knowledge of "single" frequency fade depth statistics are quite suitable for narrow band systems but inadequate for predicting the performance of high capacity digital radio links.

The GPT digital performance modelling approach utilising the equipment signature, hop parameters and the atmospheric characteristics (and embracing flat and selective fading occurrence probabilities) leads to a more reliable estimation of outage. Further, by embracing equation (3) of ITU-R Report 338-6 [4], the model is potentially transportable to engineer radio paths in climatic zones around the world.

GPT acknowledges that there is a need for more propagation measurements to be collected on a world wide basis on all types and configurations of digital radio systems. There is also an urgent need to study the probability of the coincidence of flat and selective fades in the "worst month".

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