

RECOMMENDATION ITU-R F.1106

EFFECTS OF PROPAGATION ON THE DESIGN AND OPERATION
OF TRANS-HORIZON RADIO-RELAY SYSTEMS

(Question ITU-R 103/9)

(1994)

The ITU Radiocommunication Assembly,

considering

- a) that the effects of propagation are crucial in the design and operation of trans-horizon radio-relay systems;
- b) that transmission characteristics can be determined in terms of the amplitude and phase properties of a received signal;
- c) that amplitude variation as a function of time consists of a rapid variation superimposed on a slow change;
- d) that rapid variations, which are basically caused by multipath phase interference phenomena, can be mitigated in many cases by diversity techniques;
- e) that the effects of slow variations of received power may be minimized through the use of high-power transmitting equipment, high-gain antennas, e.i.r.p. automatic level control, very low-noise receiving systems, low-loss feeders, adaptive message-loading techniques, and improved detection and other practices for system optimization, which are associated with the choice of radio-frequency carrier, bandwidth and modulation,

recommends

1. that the guidance contained in Annex 1 should be taken into consideration in the design and operation of trans-horizon radio-relay systems (see Notes 1 and 2);
2. that, in particular, the following factors should be taken into consideration in the design and operation of digital trans-horizon radio-relay systems:
 - 2.1 the combined gain of the transmitting and receiving antennas may be less than the sum of their plane-wave gains as described in § 2 of Annex 1; this apparent drop in gain is termed “gain degradation” or “antenna-to-medium coupling loss”;
 - 2.2 Recommendation ITU-R F.698 should be referred to for the preferred frequency bands for trans-horizon radio-relay systems;
 - 2.3 diversity techniques, such as space diversity, frequency diversity and angle diversity are effective for mitigating adverse effects caused by rapid variations of a received signal, as described in § 4.1 of Annex 1;
 - 2.4 transmission bandwidth of a system utilizing diversity techniques can be estimated by the methods described in § 4.2 of Annex 1;
 - 2.5 in order to mitigate the effects of multipath dispersion on digital trans-horizon radio-relay systems, order of diversity, adaptive equalization and selection of effective modems should be taken into consideration as described in § 5 of Annex 1;
 - 2.6 in order to mitigate the effect of interference to other systems, caused by side lobe and overshoot signals under conditions of enhanced propagation, the use of automatic level control of the transmitter power, from the level received at associated distant receivers, should be considered.

Note 1 – This Recommendation applies to trans-horizon systems using tropospheric scatter but not necessarily to trans-horizon systems using other modes of propagation (diffraction, etc.).

Note 2 – Recommendation ITU-R PN.617 should also be referred to for the propagation data required for the design of trans-horizon radio-relay systems.

ANNEX 1

Factors concerning effects of propagation on the design and operation of trans-horizon radio-relay systems**1. Introduction**

This Annex is based on consideration of systems carrying a relatively small number of voice channels or a television signal.

Transmission characteristics can be defined in terms of the amplitude and phase properties of a received signal. Given a tropospheric-scatter path, both amplitude and phase transmission characteristics vary with frequency and time.

Amplitude variation as a function of time consists of a rapid variation superimposed on a slow change. Rapid variations, which are basically caused by multipath phase interference phenomena, can be mitigated in many cases by diversity techniques. The effects of slow variations of received power may be minimized through the use of high-power transmitting equipment, high-gain antennas, very low-noise receiving systems, low-loss feeders, adaptive message-loading techniques, and improved detection and other practices for system optimization, which are associated with the choice of radio-frequency carrier, bandwidth and modulation.

2. Drop in antenna gain

The combined gain of the transmitting and receiving antennas may be less than the sum of their plane-wave gains. This apparent drop in gain is termed "gain degradation" or "antenna-to-medium coupling loss". Theoretical analyses state that the amount of loss is dependent on the antenna gain and scatter angle.

The path antenna gain or total effective antenna gain over a trans-horizon system has been observed experimentally to be practically independent of distance between about 150 and 500 km. According to these experiments, the total effective gain (see Fig. 1) may be assumed to depend only on the sum of the free-space antenna gains, without large corrections provided that neither of the free-space antenna gains exceeds about 50 dB, and the gains of the two antennas do not differ greatly.

Further studies indicate that the drop in antenna gain is related to the slope of the refractive index gradient-altitude curve within the common volume, consequently the variations of drop in antenna gain as a function of distance depend slightly on the climate. These studies also show that, with increasing antenna gain, the slope of the curve in Fig. 1 tends asymptotically to 1/4.

3. Choice of frequency band

The choice of a frequency band for a trans-horizon radio-relay link depends on:

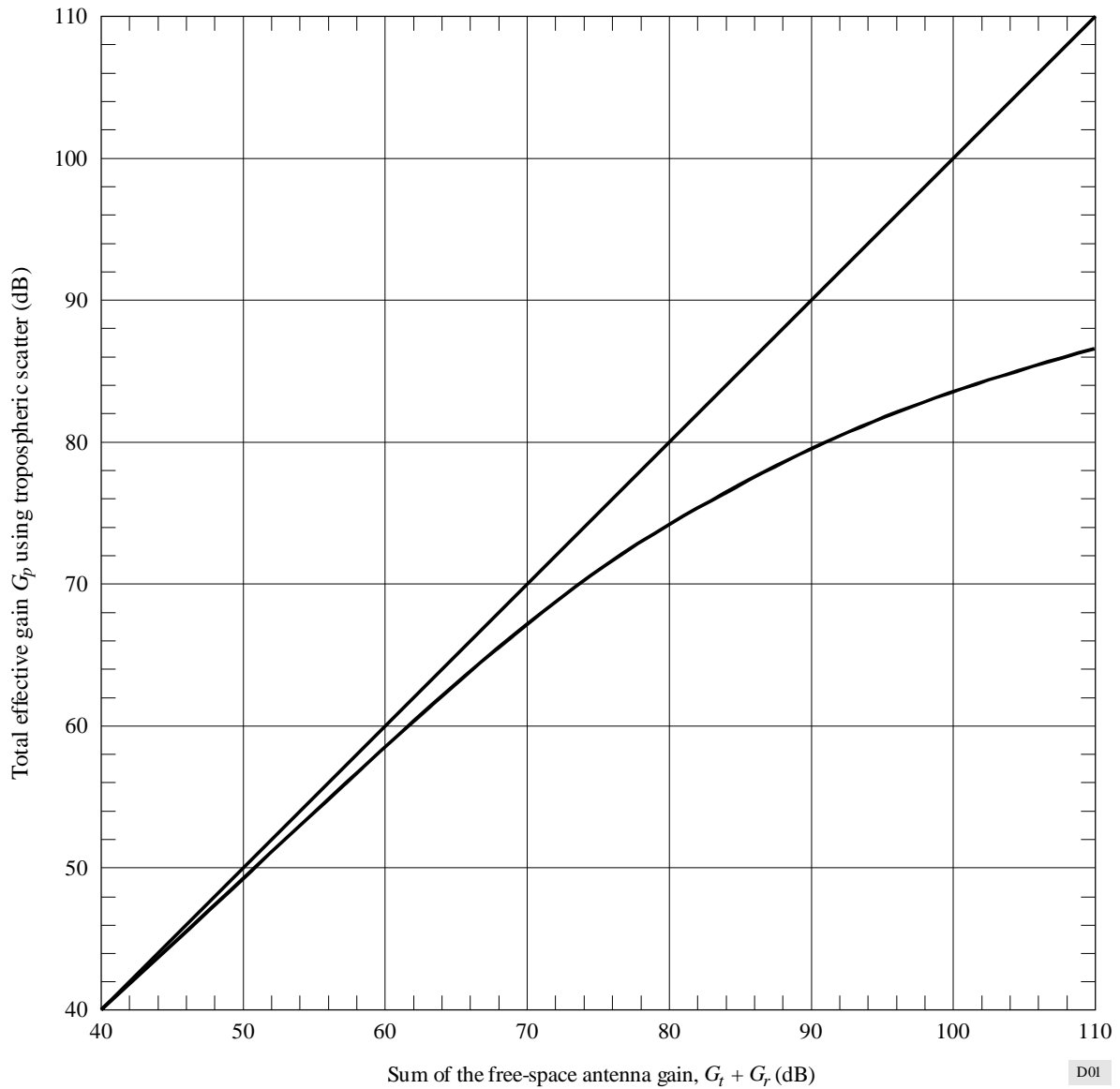
- propagation considerations, to obtain a sufficient received level and an adequate transmitting bandwidth;
- frequency sharing considerations, in relation with the usual high transmitting power trans-horizon systems.

These problems are described in Recommendation ITU-R F.698.

4. Diversity reception in trans-horizon radio-relay links

Most trans-horizon systems are designed to minimize the adverse effects of fluctuations due to propagation by making use of the partially correlated properties of the transmitted signal through diversity reception and/or transmission. Diversity techniques are also very useful for trans-horizon digital radio-relay systems because they can lead to a reduction of short-term outages which are caused by multipath fading.

FIGURE 1
Relations between antenna gains (tropospheric scatter)



DOI

4.1 *Methods of obtaining diversity signals*

4.1.1 *General*

The most commonly used methods are frequency and space diversity, i.e., simultaneous transmission of the same signal over two or more channels (frequency diversity) and utilizing two (or more) antennas for reception and/or transmission (space diversity). Some operational systems have used a combination of frequency and space diversity. Diversity reception, making use of relatively uncorrelated properties of the direction of arrival, has been also demonstrated to be beneficial in minimizing not only the rapid-fading problem, but also in lessening antenna-to-medium coupling loss.

To realize substantial operational benefits from diversity reception, low orders of correlation coefficient are not required.

4.1.2 *Space diversity in tropospheric-scatter systems*

For space diversity, the theoretical diversity distances have been examined, in terms of the horizontal correlation distance D_h normal to the path, the horizontal correlation distance D_a parallel to (along) the path and the vertical correlation distance D_v . D_h is the parameter most often utilized, expressed as:

$$D_h = 3 \lambda a / 4d \quad (1)$$

where:

d : path distance

a : equivalent radius of the Earth

λ : wavelength.

Many tropospheric-scatter systems have been installed utilizing $D_h = 100 \lambda$.

4.1.3 *Frequency diversity in tropospheric-scatter systems*

The frequency correlation coefficient between the envelopes of two signals has been found theoretically to be:

$$\rho (f_2 - f_1) = \exp \left[- (2 \pi \sigma)^2 (f_2 - f_1)^2 \right] \quad (2)$$

where:

$$\sigma = 2l (\sin (\theta / 2) / c)$$

where:

θ : angle of scatter

c : velocity of light

l : standard deviation of each dimension of the scatter volume (assuming three dimensional rectangular coordinates); l is a function of geometric and radiometeorological parameters.

The subject of frequency correlation has received more experimental attention than space correlation. Frequency correlation is important both in assessing bandwidth capability and as a design parameter for frequency-diversity systems. The minimum necessary frequency separation depends on beamwidth of the antennas and the length of the path. A frequency separation of 3 MHz was adequate to produce a correlation coefficient of 0.6 or less on 226 km and 345 km paths at either 600 or 2 120 MHz, using a 10 m antenna for transmitting and a 3 m antenna for reception.

4.1.4 *Angle diversity in tropospheric-scatter systems*

Angle diversity is a useful method which enables maximum use of a limited frequency band. Some United Kingdom test results between 1.7 and 2.7 GHz over paths of 250 to 350 km show that with antennas in the range 18 to 25 m in diameter, correlation coefficients of 0.2 and 0.4 are obtained with two radio beams separated by approximately one beamwidth, with the lower figure resulting from vertical angle diversity. These results agree closely with theory. A significant medium-term decorrelation was apparent from the trials, as was a marked tendency for the short-term cross-correlation coefficient between beams to fall with decreasing signal levels. The former effect is unique to angle diversity. The overall performance of a correctly engineered angle diversity link can be expected to approach that of frequency diversity despite the small increase in transmission loss attributable to necessary engineering compromises.

Theoretical considerations predict that angle diversity achieves most effective results at large scatter angles.

Further confirmation of the efficiency of angle diversity was obtained in trials in Japan at 1.8 GHz over a 256 km path with 19 m diameter antennas (gain = 47.5 dB), where correlation coefficients of less than 0.4 were obtained for beam separations more than about 6 mrad.

4.2 Considerations of transmission bandwidth

In estimating the effects of diversity on transmission bandwidth and quality, it is convenient to characterize the transmission system by a network having amplitude/frequency and phase/frequency characteristics which vary in a random manner with time.

A theoretical evaluation of the linear amplitude dispersion, z , can be made by assuming a Rayleigh distribution of the signal amplitude at the edge of the passband. The probability, $z < Z$ for non-diversity reception can be shown as follows, where Z shows the given value of the linear amplitude dispersion.

$$P(z < Z) = 1 - \frac{1 - Z^2}{\sqrt{(1 + Z^2)^2 - 4rZ^2}} \quad (3)$$

where:

r : bandwidth correlation factor,

$$r = \exp \left[- \left(\frac{\Delta f}{\Delta f_0} \right)^2 \right]$$

where:

Δf : bandwidth.

For troposcatter radio-relay links:

Δf_0 : the correlation passband

$$\Delta f_0 = \frac{ac}{d^2 \alpha}$$

a : effective radius of the Earth

c : velocity of light

d : path length

α : beamwidth of the antenna at the half-power points.

For diversity reception of order N , the probability of P_N for $z < Z$:

$$P_N(z < Z) = \Phi \left(\sqrt{\frac{\pi N}{4 - \pi}} \right) - \Phi \left(\sqrt{\frac{\pi N}{4 - \pi}} \times \frac{1 - Z}{\sqrt{Z^2 - 2rZ + 1}} \right) \quad (4)$$

where:

$$\Phi(y) = \frac{2}{\sqrt{2\pi}} \int_0^y \exp(-t^2/2) dt \quad (\text{the error function})$$

Measurements to verify the theoretical work have been reported in the experiment for $\Delta f = 0.5$ MHz, $z < 0.7$ for 30% of the time without, and 3% of the time with, (dual) diversity. Higher orders of diversity are expected to demonstrate additional improvements.

For systems using frequency-division multiplex, the behaviour in the passband of the transmission path can result in the production of intermodulation noise in the transmitted telephone channels. This noise varies with time and often results in noise spikes. It has been shown that the use of diversity can reduce the probability of occurrence of such intermodulation noise spikes.

A comparison of calculated and measured intermodulation noise caused by multipath propagation showed a satisfactory agreement. The measurements were made on the tropospheric-scatter path, the length of which was 303 km with an antenna beam-angle of 1° .

5. The effects of multipath dispersion on the performance of digital trans-horizon systems

5.1 *General effects of time dispersion of multipath*

The multipath dispersion over a digital trans-horizon link is considerably worse than the corresponding dispersion over a line-of-sight link for a given frequency band. Consequently the onset of multipath dispersion rather than signal-to-noise ratio as the limiting factor in communications performance, occurs at a lower transmission rate for trans-horizon links than for line-of-sight links.

A significant improvement in the performance can be obtained by intrinsic diversity improvement using adaptive equalization.

Predictions of:

- the increase in error probability due to multipath dispersion for a given set of equipment and path parameters; and
- the improvements in diversity performance and/or the reduction of intersymbol interference that can be achieved by adaptive equalization,

are expressed with respect to σ , the r.m.s. standard deviation of the delay time which is obtained by expressing the power impulse response of the trans-horizon path as a probability density function.

5.2 *Performance predictions and measurements*

The average bit error probability P_e in a digital trans-horizon link subject to multipath dispersion is dependent on the following parameters:

$2\sigma/T$: the normalized multipath dispersion, and

W : (energy per bit/noise spectral density) per diversity channel

where:

T : symbol period.

For “weak multipath dispersion” ($2\sigma \ll T$) no special protection against intersymbol interference is required as normal multiple diversity reception techniques guarantee the requisite probability level of irreducible errors.

In the case of “medium multipath dispersion” ($2\sigma < T$) passive measures against anti-symbol interference are used in addition to diversity reception. A combination of various passive methods with matched filtering of the multipath signal characterizes the active methods used to combat intersymbol interference when the elimination of intersymbol interference is accompanied by the effect of implicit diversity in multipath dispersion.

With “strong multipath dispersion” ($2\sigma > T$) the intersymbol interference can only be combatted by using special adaptive methods of reception.

In practice, both short-term and long-term variations are observed in the multipath dispersion. Measurements performed in the United Kingdom indicate that for a median 2σ value of 106 ns, the standard deviation of the long-term variation in 2σ taken from 92 s averages of 10 ms samples was 15 ns. The standard deviation of the short-term variation in 2σ taken from the 10 ms samples was 50 ns. For the 124 km test link transmitting 2 048 kbit/s with 4-CPSK, the median value of $2\sigma/T$ was 0.1.

5.3 *Transmission methods for increasing the equivalent order of diversity*

With a relatively low bit rate in the allocated frequency band, parallel or sequential multi-frequency signals can be used for each transmitter.

Parallel multi-frequency signals are used to create a lattice of equidistant frequencies by means of additional frequency modulation, and on this basis it is possible to achieve additional reception diversity, for example, triple diversity reception.

Sequential multi-frequency (generally quadruple frequency) signals can be used for dual or quadruple frequency-time diversity in combination with combined frequency and phase shift keying.

A combination of known effective codes and bit interleaving for error decorrelation is considered as a variant of the time diversity technique. However, this method of improving performance is accompanied by considerable delays in the transmission of information.

5.4 *Adaptive equalization*

The use of adaptive equalization reduces intersymbol interferences and thereby increases the transmission capacity of digital trans-horizon systems. Adaptive equalization permits the diversity inherent within multipath dispersion to be accommodated in receiver design thereby resulting in a predictable improvement in error performance for a given value of σ .

Ideally, adaptive equalization (linear equalization) in a multipath radio channel presupposes a cascade connection of the filter matched with the incoming signal and the transversal filter. However, in real conditions the input filter is matched with the transmitted signal so that, with the elimination of the influence of multi-symbol interference, the implicit diversity effect cannot be adequately achieved.

The use of decision-feedback is a non-linear method of signal processing and it can be used to compensate for the intersymbol interference caused by precursor signal elements.

Reception with evaluation of a discrete sequence by means of the Viterbi algorithm is considered to be a method for solving, with a maximum of *a posteriori* probability, the problem of evaluating the sequence of a time discrete Markov process with a finite number of states. When account is taken of the matched filtering of the multipath signal, the Viterbi algorithm is considered to be the method that offers optimum signal reception in a multipath communication channel.

Spectral processing of a multipath signal involves extracting a number of signal frequency bands at the receiving end when the signal spectrum is wider than the frequency correlation bandwidth of the communication channel. Combining signal samples in the frequency range with specific weighting coefficients makes it possible not only to eliminate intersymbol interference but also - with matched filtering of the output component signal - to achieve an implicit diversity effect.

Successful transmission of information rates of up to 12.6 Mbit/s at 4.6 GHz using adaptive modems over trans-horizon links has been reported.

5.5 *Comparative evaluation of effective modems*

A comparative assessment of the basic effective modems used to implement the various transmission methods discussed above is given in Table 1.

To evaluate the noise immunity of the method, the ratio between the mean power of the received signal and the spectral noise density was determined for a given information bit rate with a bit error probability of 10^{-6} . Quadruple space-frequency diversity reception (two transmitters, two antennas) was considered in all cases. The signal-to-noise ratio corresponds to the equivalent diversity order. The parameter β is determined, which characterizes the ratio between the mean signal power and the spectral noise density per one bit of transmitted information. The parameter γ is defined which characterizes the specific information bit rate.

TABLE 1

No.	Features of transmission method	Parameters		
		Information bit rate (Mbit/s)	β (dB)	γ (bit/s) (Hz)
1	Coherent reception of frequency-time diversity signals with adaptive offset	0.5-1	7	0.05-0.1
2	Reception of component frequency equidistant signals 2DPSK	0.5-2	7	0.08-0.3
3	Matched filtering of multipath signal using Viterbi algorithm and Golay code (24, 12) with interleaving	5	7	0.5
4	Adaptive decision-feedback equalization	5-10	12	1
5	Spectral processing of multipath 2DPSK signal	5-10	10	1
