

RECOMMENDATION ITU-R F.752-1

DIVERSITY TECHNIQUES FOR RADIO-RELAY SYSTEMS

(Question ITU-R 106/9)

(1992-1994)

The ITU Radiocommunication Assembly,

considering

- a) that frequency-selective fading may distort and reduce the strength of received signals on line-of-sight and trans-horizon paths and thereby impair the performance of a radio-relay system;
- b) that the application of diversity techniques is useful in reducing the effects of fading on system performance;
- c) that the provision of diversity reception is necessary to achieve satisfactory performance on diffraction and trans-horizon paths;
- d) that various techniques for implementing diversity on line-of-sight, diffraction and trans-horizon paths have been studied and are in use;
- e) that the application of diversity techniques can provide high performance in line-of-sight systems that make efficient use of the radio spectrum,

recommends

- 1. that the information presented in Annex 1 should be used when considering the application of diversity techniques to radio-relay systems;
- 2. that the choice of diversity techniques for a radio-relay system should include the following considerations:
 - 2.1 there are many methods of obtaining diversity signals in radio-relay systems. The common methods are described in § 1 of Annex 1;
 - 2.2 there are many methods of processing the diversity signals in radio-relay systems. The basic arrangements and implementation considerations for some of them are considered in § 2 of Annex 1;
 - 2.3 the application of various types of diversity and diversity combining techniques to trans-horizon systems are considered in § 3 of Annex 1. Additional information on the calculation of their performance may be found in Recommendation ITU-R PN.530;
 - 2.4 in applying diversity techniques on line-of-sight paths, both signal power loss and signal distortion must be taken into account, particularly for digital radio systems. These considerations are described in § 4.1 and 4.2, respectively, of Annex 1;
 - 2.5 the effectiveness of various diversity techniques in line-of-sight systems is supported by propagation studies in § 4.3 and 4.4 of Annex 1. The detailed characterization of the effectiveness of diversity propagation for line-of-sight systems may be found in Recommendation ITU-R PN.530. A summary of the measured experience with various diversity techniques in operating digital radio systems is given in Recommendation ITU-R F.1093.

Note 1 – Techniques of diversity using alternative transmission media or route diversity, which are applied to improve availability, are not treated in this Recommendation.

Diversity techniques for radio-relay systems

1. Methods of obtaining diversity signals

The most common methods are generically described as frequency diversity and space diversity. In frequency diversity, the same information is transmitted over more than one radio channel. In space diversity, the signal reaches the receiver through more than one transmit/receive antenna path. A description of diversity implementation in different systems operating in distinctive propagation regimes requires a more detailed description of space diversity methods.

Trans-horizon systems have used space diversity on both transmit and receive. They use multiple diversity with full, three-dimensional, flexibility in the placement of antennas, and sometimes use angle diversity in which multiple beams or directivity patterns are formed with a single antenna. Angle diversity provides relatively uncorrelated signals by taking advantage of the variations in the angle of arrival of the scattered energy at the receiver.

On line-of-sight paths, space diversity is usually implemented using two antennas at the receiver with a large enough vertical separation to provide two signals in which the impairments due to multipath fading are sufficiently decorrelated, where the impairments are signal distortion and loss of signal power. Concerns for the performance of digital radios, for which signal distortion is the dominant propagation impairment, have led to the introduction of diversity methods that rely on the non-uniform structure of the incident electromagnetic field near the main receiving antenna, instead of large spatial separations, to decorrelate the signal impairments.

In these methods, which are called pattern diversity or angle diversity, the diversity signal is derived from a second antenna or beam that has a different directivity pattern or angular beamwidth in the vertical dimension and/or a different boresight elevation angle. These diversity methods, which can be implemented with antennas that are at the same, or nearly the same, height or with multiple feeds within a single antenna, allow diversity to be added to an existing hop without requiring tower height extensions to obtain path clearance for diversity reception. Although some workers attempt to distinguish between angle and pattern diversity, others use the terms interchangeably.

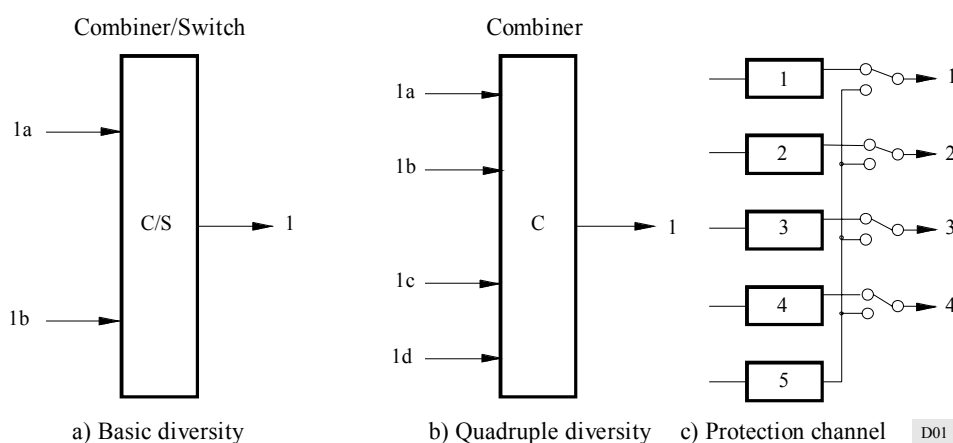
Since the effectiveness of any diversity system depends on the correlations of the impairments in the signals, the displacements in space, pointing angles, and frequency are fundamental in determining system performance.

2. Methods of processing signals

2.1 Arrangements

Figures 1a) and 1b) show the basic arrangements in which two or four signals are used to derive a common output or decision, in the case of some digital systems. Although systems in line-of-sight paths often use frequency diversity to implement 1 + 1 protection switching with the arrangement of Fig. 1a), it is more common to use one or sometimes two protection channels for several working channels. Figure 1c) shows the arrangement for a 1 + 4 operation. Such protection is often applied in tandem with space diversity operation on the individual channels. Under extreme conditions, such as those sometimes encountered on reflecting line-of-sight paths, space diversity is used in conjunction with 1 + 1 frequency protection. Difficult long or over-water paths have also used quadruple diversity, either in the form of quadruple space diversity or in a combination of dual space and dual frequency diversity.

FIGURE 1
Arrangements for diversity combining



2.2 Implementation considerations

Current systems implement diversity operation by using combiners at radio, intermediate, or baseband frequencies, or by using switches at intermediate or baseband frequencies. These combiners may employ equal gain, maximum power, or minimum dispersion control algorithms. Because the differences in the transmission performance are small, the equipment design choice between these alternatives is usually based on convenience or simplicity. Whether diversity is needed on a given link is determined by the expected severity of propagation conditions and by the characteristics of the transmitted signal.

The actual improvement which can be obtained from diversity depends upon many parameters, which include the influence of in-band amplitude dispersion and inter-system interference on channel performance, and the algorithms which are used in the implementation of diversity.

In high speed digital radio-relay systems, use has been made of minimum dispersion combining devices (MID) and also of dual reception receivers in which the diversity signals are processed by maximum power combining (MAP) and the aggregate signal by adaptive equalizing (EQ). The use of MAP + EQ produces a synergistic effect, i.e. a considerable decrease in the bit error rate. Further information about this synergistic effect can be found in Recommendation ITU-R F.1093. The methods used for combining space diversity signals on the basis of the maximum power principle which are used in receivers with MAP + EQ can be classified into the following three categories:

- MAPEG or maximum power equal gain combining. This method which uses linear addition has the following drawback: in the case of complete fading of one of the diversity signals, the signal/noise ratio at the combiner output is 3 dB worse than with an ordinary receiver.
- MAPEG/SW or maximum power equal gain/switch combining. This method uses linear addition and there is no signal/noise ratio loss at the combiner output when the input signal from the first receiver is switched off when it becomes $(\sqrt{2} + 1)$ times weaker than the input signal from the second receiver. This method has the following drawback: when switching takes place, a transient process occurs which gives rise to an increase in the error ratio in high speed digital systems.
- MAPOPT or maximum power optimized combining. This method does not suffer from the drawbacks inherent in the MAPEG and MAPEG/SW systems. In the MAPOPT system, the diversity branches in front of the combiner contain electronic attenuators, the attenuation of which varies automatically in proportion to the ratio of the powers of the space diversity signals received. In a MAPOPT combiner, linear addition occurs when there is a strong/weak

signal power ratio of $\gamma < 7.7$ dB; if further fading occurs, smoothly varying attenuation proportional to the parameter γ is introduced into the weak signal path. The signal/noise ratio gain for MAPOPT in comparison with that of an ordinary receiver is practically equal to the gain as defined by an optimum addition combiner (maximum ratio combining or MAR).

With reference to the minimum dispersion combining devices (MID) also used for combining space diversity signals, the following method can be considered:

2.3 Minimum BER or weighted strategy

This method is based on a proper weighting of the received IF (or BB) signals and in-band dispersion in order to minimize the bit error rate (BER).

The BER function can be estimated in real time from the received level and in-band power dispersion (IBPD) of the signal. Optimization of the estimated BER is equivalent to optimization of the radio link hop outage.

3. Applications in trans-horizon systems

3.1 Types of diversity

Existing systems use space diversity, angle diversity, and frequency diversity, either singly or in combination, to obtain sufficiently decorrelated replicas of the transmitted signal. For more detailed information on the application of these techniques and the calculation of their performance, reference should be made to Recommendation ITU-R F.1101.

3.2 Types of combiners

Trans-horizon systems have commonly employed combiners following demodulation. The types of combiners in order of decreasing efficiency are maximal-ratio, equal-gain, and selector. Equal-gain combining can result in equipment and maintenance simplification over maximal-ratio combining, at only a modest sacrifice (about 1 dB for quadruple diversity) in performance. A further narrowing of this gap can be achieved by combining equal-gain with selector diversity-combiners. With equal-gain combining, if the signal levels differ greatly, a receiver in a weak signal leg can actually degrade overall performance; however, if it is switched off under these conditions, the overall performance closely approximates an ideal maximal ratio combiner.

4. Applications in line-of-sight systems

Multipath fading on line-of-sight paths results in a loss of power which may vary selectively within a radio channel. These two aspects, loss and dispersion, can be considered separately in some applications. For FM and narrow-band digital signals, performance is controlled by narrow-band, or single-frequency, power loss; for many high capacity digital systems, dispersion controls performance. Because of the rapid evolution of high capacity digital radio systems, it is difficult in a given application to identify which systems are sensitive only to loss, which only to dispersion, and which to both. Although higher multi-state modulations are inherently more sensitive to dispersive effects, equipment design advances, such as those obtained with improved equalizers, make systems less sensitive to dispersion.

4.1 Single-frequency signal power loss considerations

On line-of-sight systems during periods of multipath fading, the signals received by two vertically separated receiving antennas rarely fade simultaneously when the fades are deep. The available improvement from such a pair of antennas can be defined as a ratio I_0 , in which the numerator is the time for which the signal from the main receiving antenna is below the fade margin and the denominator is the time during which the signals from the two antennas are below the margin simultaneously. Let P be the fraction of a month of high fading activity during which the received

signal in an unprotected radio channel has a value less than a particular margin. Then, the fraction of time during which the space-diversity protected signal on this link has a value less than that fade margin is P divided by I_0 , when a perfect switch is used that will always select the stronger of the two received signals.

For an ideal switch which always selects the stronger of the two received signals, the space diversity improvement factor has been empirically related to the fade level, path length, frequency, and relative antenna gains for paths where ground reflections are negligible.

The improvement factor obtained using a combiner may be larger than that of an ideal switch owing to the coherent addition of signal power, but depends on the method of controlling the combiner. For maximum-power equal-gain combining, in which only the relative phase of the input signals is controlled, the theoretical improvement factor is 3/2 that of the ideal switch.

4.2 Dispersion considerations

Both diversity combiners and diversity switches have been used to reduce the effective incidence of dispersive fading effects in high capacity digital system and single-sideband AM systems. For space and angle diversity applications both maximum power and minimum dispersion control algorithms have been evaluated. The combiners apply a relative phase shift to the input signals and coherently add them to achieve their design objective: maximizing the output signal power for a maximum power combiner; flattening the amplitude frequency response of the output signal for a minimum dispersion combiner.

Frequency diversity applications usually employ baseband switches to select, ideally without errors, the signal with the lower BER.

Evaluations of diversity techniques to reduce dispersion have been based on the observed operation, or partially simulated operation, of systems under field test conditions, and on propagation tests in which linear amplitude dispersion (LAD) or in-band power difference (IBPD) was measured. LAD is the decibel difference between the attenuation measured near the two edges of the power spectrum of the signal; IBPD is the decibel difference between the smallest and largest attenuation measured in the bandwidth of the signal. The use of LAD and IBPD is based on field test data indicating a good correspondence between the occurrence of these quantities and the occurrence of high bit error ratios.

4.3 Evidence from propagation data

Existing systems use space diversity, angle diversity, and frequency diversity, either singly or in combination to obtain sufficiently decorrelated replicas of the transmitted signal.

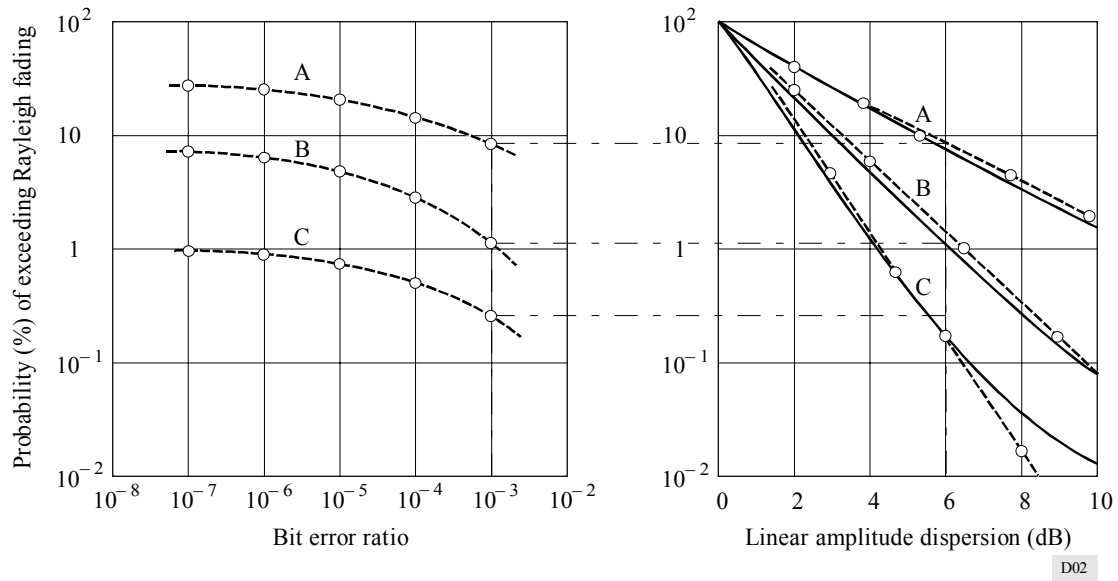
4.3.1 Space diversity

In one experiment, high capacity digital radios were equipped with both maximum power and minimum dispersion combiners. The minimum dispersion combiner determined the frequency response by measuring the spectrum shape; however, when the combined signal fell below a predetermined level, the minimum dispersion combiner was operated as a maximum power combiner. Figure 2 gives both calculated and experimental results, with a 16-QAM system, and shows the improvement in LAD probability for both combiners and for non-diversity operation.

Space diversity on line-of-sight radio-relay systems has been engineered with vertical antenna spacings usually greater than 5 m, the minimum spacing for which the formulae for single-frequency space diversity improvement factors are applicable (see Recommendation ITU-R PN.530). Although these formulae would imply a decrease with smaller spacings, recent results indicate substantial improvements with small spacings when the antennas have different vertical directivity patterns. Furthermore, a digital radio simulation suggests that the diversity improvement may not decrease uniformly to zero even when the antennas are identical, because of the interaction of the antenna patterns with the incident field. Since pattern differences affect both the single-frequency and dispersive improvement factors, diversity spacings with small separations should be regarded as a form of pattern diversity until a comprehensive formulation of improvement factors is developed for the various cases.

FIGURE 2

Diagram showing the effect of space diversity on the linear amplitude dispersion probability on a single-hop 16-QAM system (53 km over-sea hop, in Japan, 5 GHz, 200 Mbit/s, 50% roll-off factor, no adaptive equalizer)



- A: non-diversity
 B: maximum power combiner
 C: minimum dispersion combiner
 ○---○ measured
 — calculated

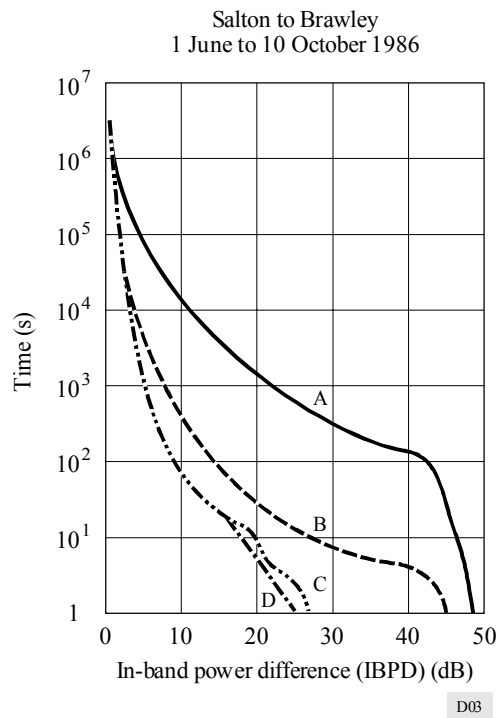
4.3.2 Pattern or angle diversity

An early study, which implemented pattern diversity by coupling to two different modes in a receiving horn antenna, showed only modest diversity improvement for single-frequency fading using switched diversity. The potential for the significant diversity improvement that was noted in an experiment monitoring co-channel cross-polarized operation of 4-PSK digital radios was attributed to the difference between the vertical and horizontal directivity patterns of the transmitting and receiving antennas. In a study on a long (105 km) overwater path, measurements of the power of the received signal, which was an 8-PSK, 45 Mbit/s digital signal at 7.4 GHz, showed significant improvements from angle diversity using a dual-beam antenna. Larger improvements in reducing the occurrence of multipath dispersion (IBPD) were obtained in an experiment in which two dissimilar antennas with the same boresight angle were mounted side by side. An experiment in which fading was measured with four vertically arrayed beams, over a 90 MHz bandwidth at 4 GHz on a 45 km hop, gives further support to the advantages of angle diversity.

The results from two propagation experiments, which were configured to evaluate angle diversity for high capacity digital radio applications, provide further support to the advantages of angle diversity. The first of these was instrumented at 6 GHz on a 60 km path that was known to provide a strong ground reflection under normal atmospheric conditions. Angle diversity was implemented with a dual-beam antenna, which provided sum and difference voltages as one diversity pair, and a dual beam output as a second pair. For a comparison, space diversity was monitored simultaneously with a 3 m conical horn antenna mounted 12.8 m below the main antenna. Diversity signals were

obtained by using a maximum power combiner, and fading was monitored by a three-frequency measurement of received power. The distributions of IBPD at the output of the combiners (Fig. 3) show that IBPD occurred less often with either of the angle diversity input signals than with space diversity inputs during the experiment. In subsequent periods, angle diversity reduced the outage time of a 64-QAM digital radio on this path by factors near 400.

FIGURE 3
Distributions showing the effect of angle and space diversity with maximum power combining on the occurrence of in-band power difference (measured at three frequencies in a 30 MHz band) for a 60 km path with ground reflections in the United States of America, at 6 GHz

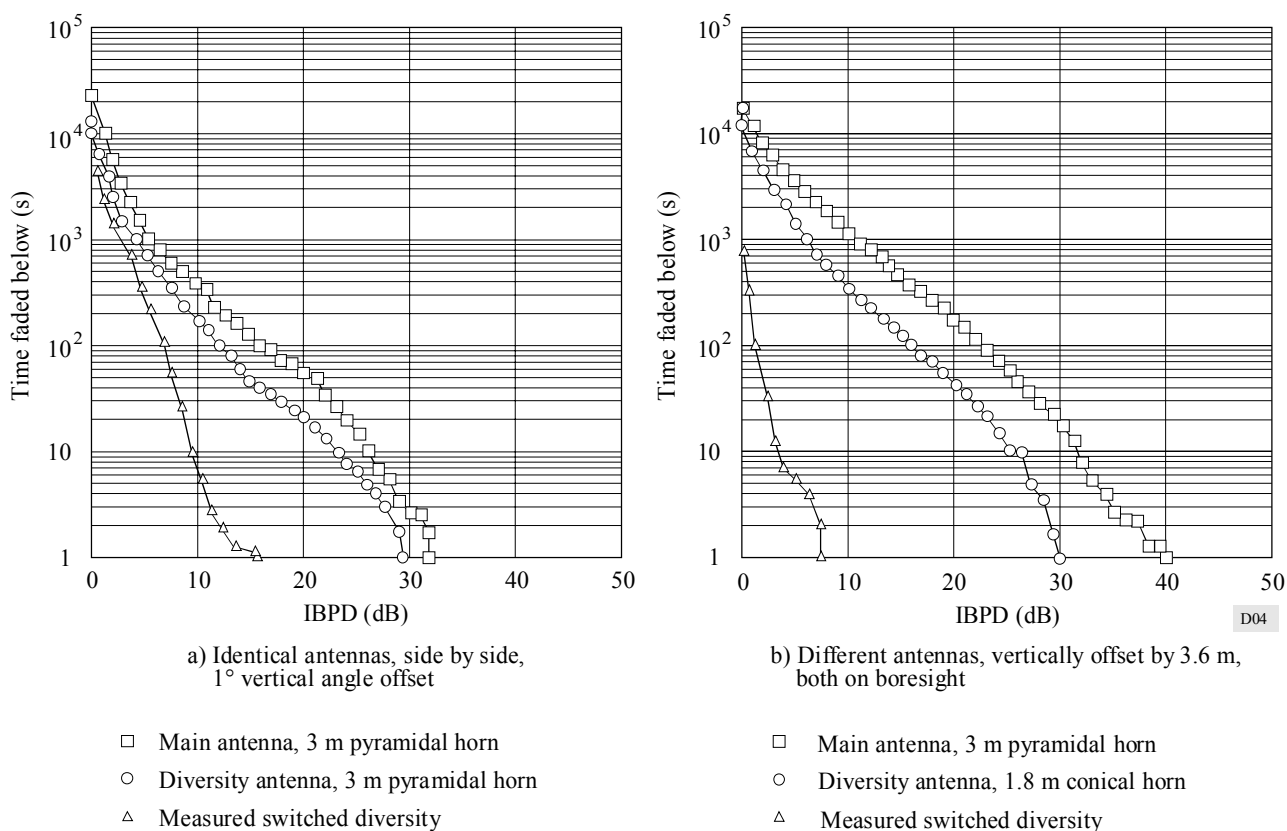


- A: main antenna, 3 m conical horn
- B: combiner with 3 m conical horn diversity antenna 12.8 m below main antenna
- C: combiner with sum and difference signals from 2.4 m dual-feed dish
- D: combiner with upper and lower beam signals from 2.4 m dual-feed dish

As part of a series of experiments to determine the effects of small angular and spatial displacements of identical and dissimilar antennas on a 38 km path in Florida, angle diversity was implemented in one test with two identical 3 m pyramidal horn antennas mounted side by side. In another experiment in the series, the diversity signal was derived from a smaller (1.8 m) second antenna located close below the main antenna on the tower. The fading was characterized by monitoring the received power at 16 frequencies in a 30 MHz band at 6 GHz. Figure 4 shows the occurrence time statistics of IBPD for the two configurations. Although both show substantial reductions in the occurrence time of IBPD, the reduction obtained with a vertical separation is significantly greater in this experiment.

FIGURE 4

Distributions showing diversity effects with ideal (minimum dispersion) switching on the occurrence of in-band power difference (measured at 16 frequencies in a 30 MHz band) for a 37 km path near Gainesville, Florida, United States of America, at 6 GHz



Propagation experiments comparing angle and space diversity have provided further useful information. In measurements on a 55 km path near Darmstadt (Germany) and similarly, on a 51 km path in the East of England, space diversity performed better than angle diversity. Measurements on a 47.8 km path near Richardson, Texas (United States of America) showed that the advantage of space diversity over angle diversity was dependent on the angle diversity configuration. A dual-beam antenna with the lower beam aimed at the nominal incident angle of arrival performed significantly better than one with the beam crossover aimed at this angle, whereas a configuration using sum and difference signals was better than the dual beam arrangement and almost as good as the space diversity arrangement. These results were supported with data from concurrent meteorological measurements.

Comparisons of angle and pattern diversity with space diversity were made in experiments in Alabama and Mississippi in the United States of America. The results, from one fading season in each location, also showed a performance advantage, in a dual-antenna configuration, from aiming one antenna above the nominal angle of arrival, and an advantage of space diversity over angle diversity. The advantage of space diversity in this case was attributed to differences in the fade margins of the radios and to differences in the dispersiveness of the fading on the hops. Based on these results and others, the following conclusion was drawn: where digital radio performance is dominated by dispersive effects, angle diversity and space diversity perform equally well; where thermal noise effects predominate, space diversity is a better choice.

A 6 GHz experiment that involved a 124 km hop with strong reflections from Lake Geneva in Switzerland resulted in extremely high improvement factors for angle diversity and somewhat lower improvements for space diversity.

In a two-year experiment in the Netherlands, dual beam angle diversity gave higher improvement if one beam was aimed below the nominal angle of arrival. In this configuration the improvement was almost the same as space diversity improvement measured on seven comparable hops.

4.3.3 Frequency diversity

Experimental evidence suggests that frequency diversity provides a more effective countermeasure against the dispersion that affects digital systems than against power loss that affects narrow-band FM systems. In one set of experiments, propagation tests were combined with measurements of the frequency diversity improvement factor for a 16-QAM, 90 Mbit/s digital radio operating in the 6 GHz band on a 42 km path from Atlanta to Palmetto in Georgia, United States of America. By processing the bit error ratio occurrences of the two digital radios, operating in channels with a centre frequency separation of 60 MHz, as the inputs to a 1 + 1 frequency diversity arrangement with an ideal switch, data from 1980 and 1982 showed frequency diversity improvement factors of 100 and 45, respectively, at a 10^{-3} bit error ratio. This improvement is comparable to the space diversity improvement factor measured at a 9 m antenna separation with the same radios on this path. In contrast, standard techniques, based on single-frequency fading, predict an improvement factor of 9 for an analogue FM radio with a fade margin between 30 and 35 dB.

An experiment, which was performed at 6 GHz with 90 Mbit/s digital radios in a 1 + 1 configuration on a 100 km path in Wyoming, United States of America, similarly showed frequency diversity improvements for digital radios that exceeded FM predictions by a factor of 10.

In an experimental evaluation of a frequency diversity arrangement using a 3 + 1 multi-line switch, an outage reduction factor of approximately 5 was achieved. The equipment comprised 11 GHz 140 Mbit/s QPSK digital radio which was installed on a single hop. The improvement would however be less for the more typical situation of a 5 + 1 switch protecting a multihop system.

4.3.4 Quadruple diversity

Work in Australia investigating quadruple diversity, either as quadruple space diversity or as a combination of dual space and cross-band frequency diversity, to satisfy high grade digital error performance and availability objectives on difficult paths, particularly long over-water paths, has reported some success with this approach. Measured improvement factors from two long over-water experiments are tabulated in Table 1.

Good improvement using quadruple space diversity on a difficult path that is subject to blackout fading has also been reported.

TABLE 1

**Improvement factors – Quadruple over dual diversity – Worst month,
typical month in brackets**

	Experiment 1 158 km	Experiment 2 116 km
Severely errored seconds	2.6 (15)	6.5 (29)
Minutes of degraded performance	1.6 (10)	6.2 (30)
Errored seconds	1.4 (7.4)	3.7 (4.5)
Unavailable seconds	2.0 (7.0)	25.0 (> 25)

4.4 Dispersion statistics

Published works have been developed that provide statistical descriptions of the dispersive effects of multipath fading. More detailed information on the experimental observation and the prediction of outage of digital radios that use diversity techniques on line-of-sight paths may be found in Recommendation ITU-R F.1093.

A theoretical evaluation of the non-diversity and diversity distributions of linear amplitude dispersion, assuming Rayleigh distributions for the individual amplitudes, has been developed in the context of trans-horizon systems. A more recent study developed predictions of the probability that linear amplitude dispersion exceeded a critical value at the output of both maximum power and minimum dispersion combiners.

Simulations of frequency diversity with a wideband three-ray model have been used to provide a simultaneous description of the selective fading in all the channels of a radio band. For a 1 + 1 arrangement this model predicts that, contrary to analogue radio-relay applications, within certain limits, the performance improvement of digital radio tends to increase as the frequency separation between the two channels decreases.
