Ingvar Henne
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Planning of line-of-sight radio relay systems

Second edition

NERA
TELECOMMUNICATIONS

The cover page illustration shows fading activity on a path in Botswana. The measurements are performed at 6.8 GHz in August 1993. Input levels for main- and space receiver are plotted with a time scale of 5 hours/page-width. The front page shows deep fades during the night, and the back shows the afternoon activity with a distinct drop in signal level at sunset.

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Preface to the second edition

Something old, something new, something borrowed and something blue. Here we go again. To our amazement all the copies of the first edition have been swept away and we have taken this golden opportunity to make a slightly enhanced version of the book. The first edition came into being in 1994 and since then there has been changes to the performance objectives, the prediction models and the way we utilise the wireless medium. The recent rapid growth in the telecommunication sector has been very favourable for radio relays. Radio relays have now found their way into both the backbone and the access network. The current trend is to use higher frequencies and more spectrum-efficient techniques. These changes are reflected in the new edition of the book. Since 1994 we have also performed some more field measurements and they have been included in to the text where appropriate under the motto: “seeing is believing”.

The following topics are new in the second edition:

- The field survey chapter (chapter 4) has been rewritten
- New recommendations (chapter 5) like
  ITU-T G.827, ITU-R F.1189, F.1092 & F.1397
- Atmospheric attenuation (chapter 7)
- New rainmaps (chapter 8)
- New ITU-R multipath fading prediction model (chapter 9)
- New ITU-R diversity models (chapter 10)
- Cross-polar interference (chapter 11)
- Survey of frequency plans (chapter 14)

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Preface

This book describes planning and engineering of line-of-sight radio relay networks. This is the second edition of a textbook on the planning issues prepared by the propagation group at Nera. Planning of line-of-sight (LOS) radio relay systems will be described in general. The main objective for system planning is to ensure that the radio relay system will meet the given performance and availability requirements. The authors would like to thank Knut Erik Lande and his colleagues for very useful comments and corrections.

The following topics will be covered:

- Wave propagation in the atmosphere
- Site location and antenna heights
- Terrain profiles
- Introduction to survey
- Performance and availability objectives
- Flat fading and selective fading
- Propagation and precipitation
- Frequency planning
- Equipment reliability

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Contents

Chapter

1

General considerations

System planning covers the determination of all main parameters of the radio relay system. This includes network configuration, system capacity, performance objectives and radio frequency band. Selection of sites, power requirements, towers and shelters will not be covered in this book.

The more detailed part of the planning covers individual path parameters like antenna heights, antenna types and sizes, performance and availability calculations, diversity configuration and frequency planning.

Wave propagation in the atmosphere and its impact on the performance of digital radio relay systems is the main topic in this book. Principles, calculation models and measurements will be introduced trying to explain the radio waves apparently unpredictable propagation through the atmosphere. The main purpose of system planning is to achieve a reliable transmission system that meets the specified international error performance and availability objectives. Understanding both the objectives as well as the prediction models is therefore very important to a system planning engineer. Performance and unavailability due to propagation effects, precipitation, interference problems and equipment failure must be evaluated.

The number of available radio frequency channels is limited. Frequency planning is therefore an important part of the system planning. The task for the system planning engineer is to select radio frequencies and antenna types in the most economical way. Future expansion of systems should also be kept in mind.

Availability of radio relay systems is a function of both propagation effects and equipment failures. The availability of radio equipment based on MTBF (Mean Time Between Failures) for equipment modules is presented. Practical experience shows that availability of the total system often is limited by other factors than the radio relay equipment itself. Unavailability due to maintenance problems, power failures, etc. may often dominate the total unavailability of the system, especially in rural areas.

Measurements from in-service radio relay systems are included to illustrate propagation models. These measurements are mainly from three paths:

Path in desert area in Botswana.
Radio frequency: 6.8 GHz Capacity: 140 Mb/s
Frequency and space diversity.

Over water path in Southern England.
Radio frequency: 7.5 GHz Capacity: 34 Mb/s
Space diversity.
This particular path is used as an example throughout most of the book.

Co-channel path in Switzerland.
Radio frequency: 4 GHz Capacity: 155 Mb/s
Space diversity

Chapter 2

Wave propagation in the atmosphere

Radio wave propagation in free space (no atmosphere) is indicated in figure 1. The radio waves follow straight lines from the radiation point. Interaction with the molecules in the atmosphere bends the radio waves as indicated in figure 2. Waves are bent towards regions with higher index of refraction (denser medium). Under normal atmospherical conditions the density of the atmosphere decreases monotonically with height above ground, so that the index of refraction decreases with height. This gives the highest index of refraction near the surface of earth, and consequently the waves are bent towards the ground as indicated in figure 2.

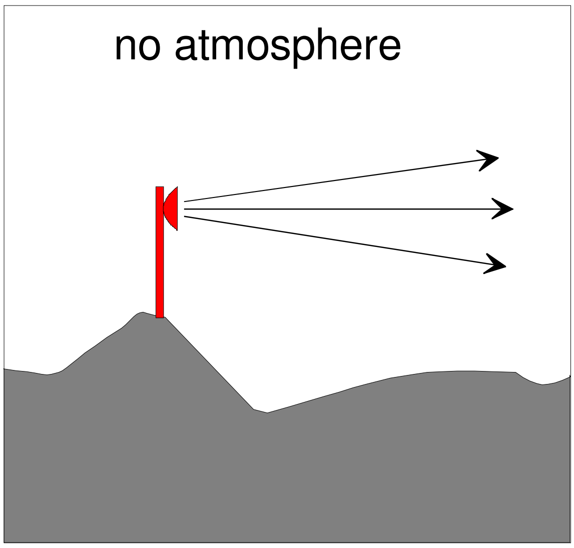


Figure 1 straight rays in vacuum

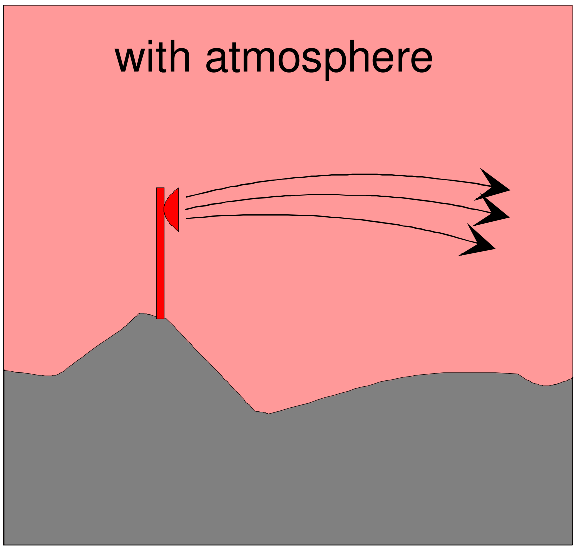


Figure 2 bent rays in atmosphere

Radio waves may be treated with ray optics. This approximation is good if the wavelength $\lambda << d$ (d is the characteristic dimension of an object). In this case the fundamental laws of ray optics may be applied.

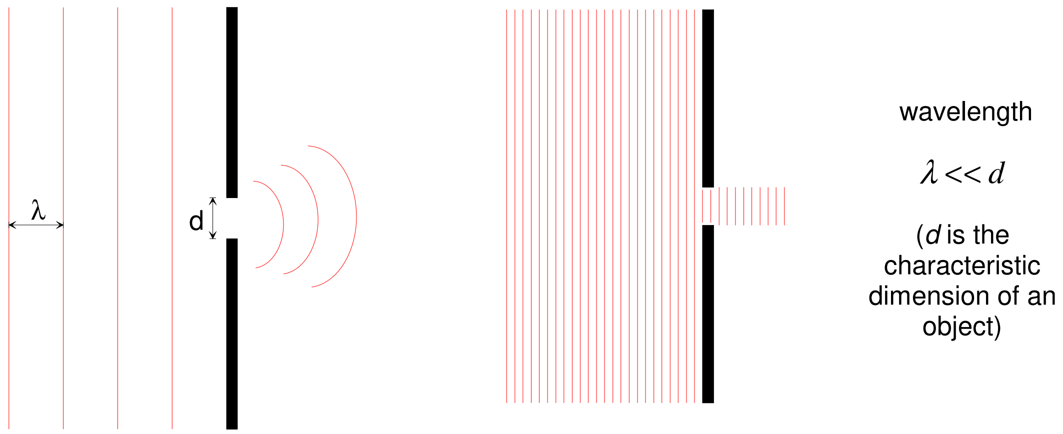


Figure 3 Wavelength and geometrical dimensions

2.1 Fundamentals of ray optics

If the observation point is far away from the radiation source, the radio waves very nearly form a plane wave front. Consider the case of a plane wave that is incident obliquely at an arbitrary angle of incidence θ_1 on a plane interface between two dielectric media. The two media are assumed to have different index of refraction, $n_1 \neq n_2$ as indicated in figure 4. Because of the medium's discontinuity at the interface, a part of the incident wave is reflected and a part is refracted. The angle of incidence equals the angle of reflection, that is $\theta_1 = \theta_1'$. The angle of incidence θ_1 is related to the angle of refraction θ_2 by Snell's law:

1) $$n_1 \cdot \sin\theta_1 = n_2 \cdot \sin\theta_2$$

where the index of refraction n_i is given by:

2) $$n_i = \frac{c}{v_i}$$

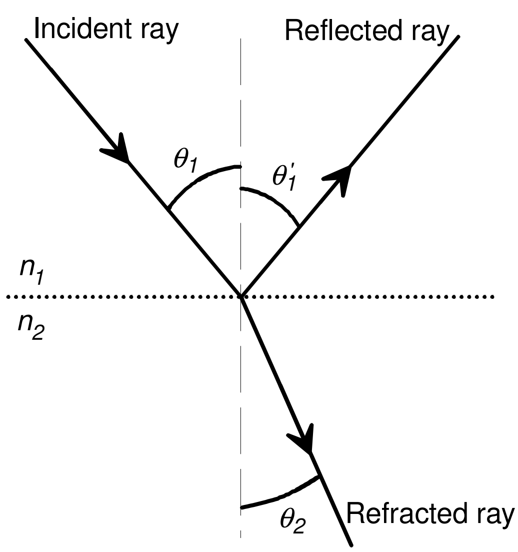
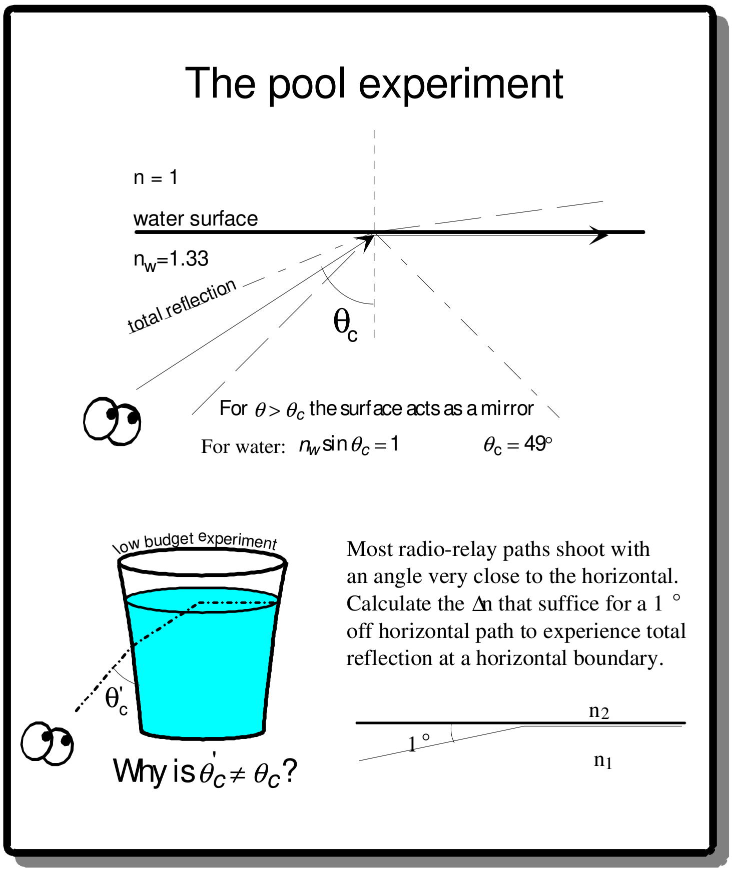
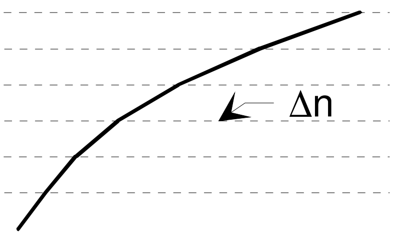


Figure 4
Geometrics of Snell's law

where c is the speed of light in vacuum and v_i is the speed of the radio waves in the given medium. [46]



Snell's law (equation 1) indicates that the rays bend towards the denser of the two media. In the atmosphere the index of refraction is varying continuously.



Consequently no distinctive boundary will be found as in figure 4. Ray bending in the atmosphere may be considered as a large number of boundaries with a small variation *Δn*.

2.2 The index of refraction for the atmosphere

The index of refraction for air, for the frequencies of interest, is very close to that of vacuum. Due to that, the radio refractivity, N, is used instead of n.

3) $$N = (n-1)\cdot 10^6$$

An empirical formula for N is

4) $$N = \frac{77.6}{T}\left(p + 4810 \cdot \frac{e}{T}\right)$$

- T is the temperature in Kelvin. (= Degrees in Celsius + 273.15)
- p is the total air pressure in hPa (= mbar)
- e is the water vapour pressure in hPa

Since p, e and T all are functions of the height, consequently also N is a function of height.

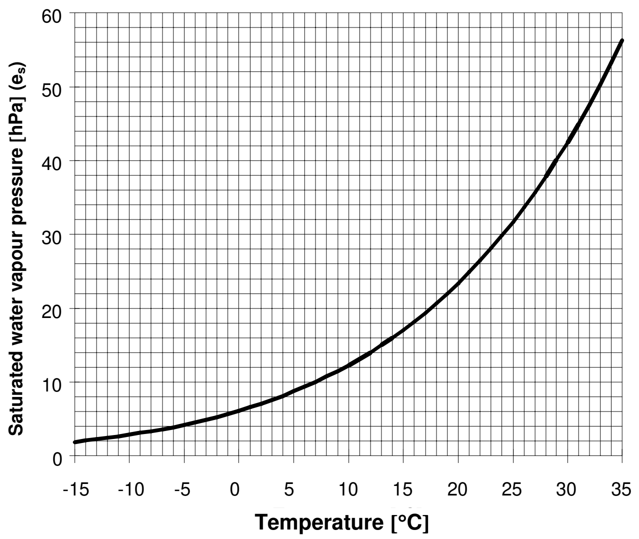
For a normal atmosphere (standard, well mixed) the variation of N with height is

5) $$\frac{dN}{dh} = -40 \frac{\text{N-units}}{\text{km}}$$

6) $$N(h) = 315 \cdot e^{(-0.136 \cdot h)}$$

where h is the height above ground in kilometre.

Calculation of e
(water vapour pressure)



$e = \frac{H}{100} \cdot e_s$ where H is relative humidity in %

$e_s = 6.1121 \cdot e^{\left(\frac{17.502 \cdot t}{240.97 + t}\right)}$ where t is temperature in ℃

This indicates that a standard atmosphere is most dense near ground so the rays bend downwards. The radius of curvature for the ray bending r is given by

7) $$\frac{1}{r} = -\frac{1}{n} \cdot \frac{dn}{dh} \cdot \cos\alpha$$

where α is the rays angle with respect to the horizontal. [38]

2.3 Ray bending relative to earth

The ray bending given in equation 7) may be referred to the physical radius of earth by an effective ray bending radius r_e:

8) $$\frac{1}{r_e} = \frac{1}{a} - \frac{1}{r} = \frac{1}{a} + \frac{dn}{dh} = \left(157 + \frac{dN}{dh}\right) \cdot 10^{-6}$$

where a is the radius of earth = 6370 km

In equation 8) one has assumed that n is nearly one and α is nearly zero.

Let us define the modified radio refractivity M such that $\frac{dM}{dh} = 157 + \frac{dN}{dh}$. If $\frac{dM}{dh} = 0$ the rays will bend at the same rate as the earth. If $\frac{dM}{dh} < 0$ the rays will bend more than the earth and a radio duct will be created.

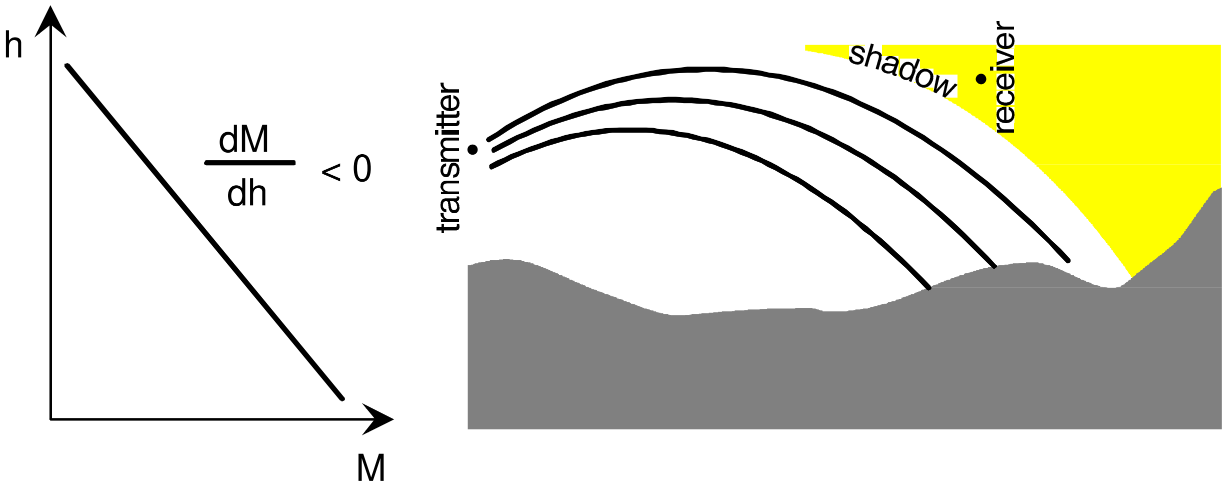


Figure 5 Radio shadow with $\frac{dM}{dh} < 0$

2.4 K-value

K-value is a common used value to indicate ray bending. The definition of K is

9) $$K = \frac{r_e}{a} = \frac{1}{\left(\frac{1}{a} + \frac{dn}{dh}\right) \cdot a} = \frac{1}{\left(1 + a \cdot \frac{dN}{dh} \cdot 10^{-6}\right)}$$

For a normal atmosphere $\frac{dN}{dh} = -40$. The corresponding k-value is thus

10) $$K = \frac{1}{\left(1 + 6370 \cdot (-40) \cdot 10^{-6}\right)} = \frac{4}{3}$$

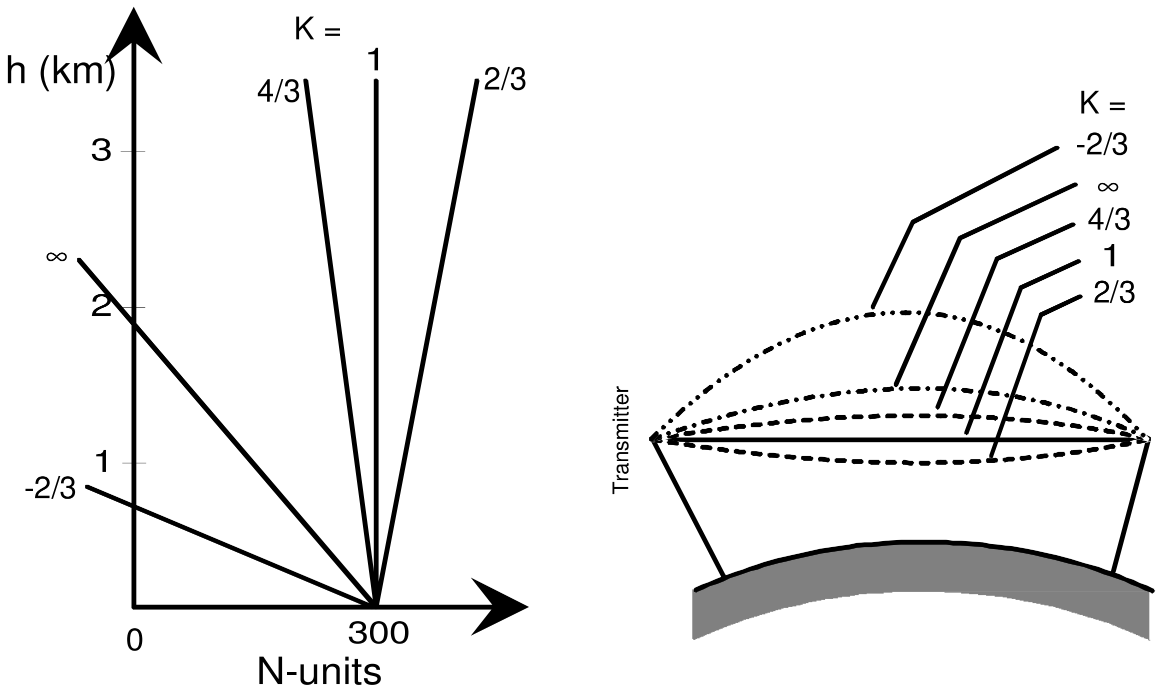


Figure 6 k-value variations

2.5 Atmospherical multipath propagation

Multipath propagation occurs when there are more than one ray reaching the receiver. Multipath transmission is the main cause of fading. Multipath can only happen when $\frac{dN}{dh}$ varies with height.

2.5.1 Ground based duct

Figure 7 shows a ground based duct. The atmosphere has a very dense layer at the ground with a thin layer on top of it. There will be nearly total reflection from this layer boundary. [47]

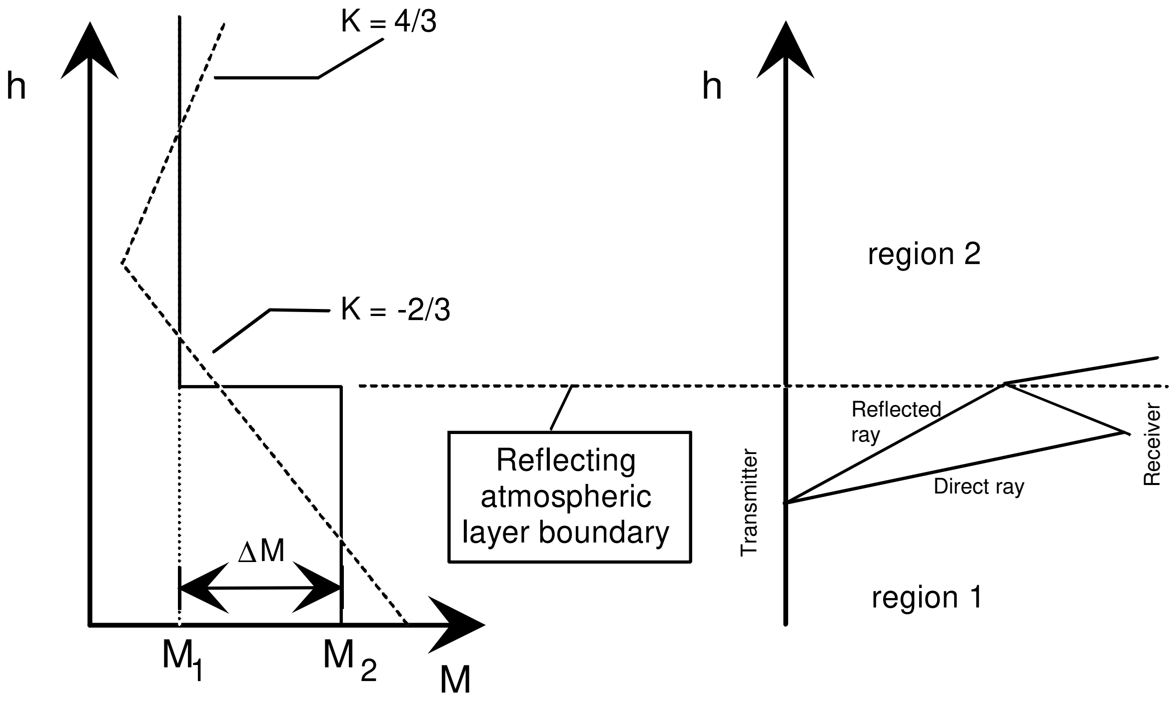


Figure 7 Ground based duct [47]

2.5.2 Elevated duct

The atmosphere has a thick layer in some height above ground. If both the transmitter and the receiver are within the duct, multiple rays will reach the receiver. If one is inside and the other is outside the duct, nearly no energy will reach the receiver. [47]

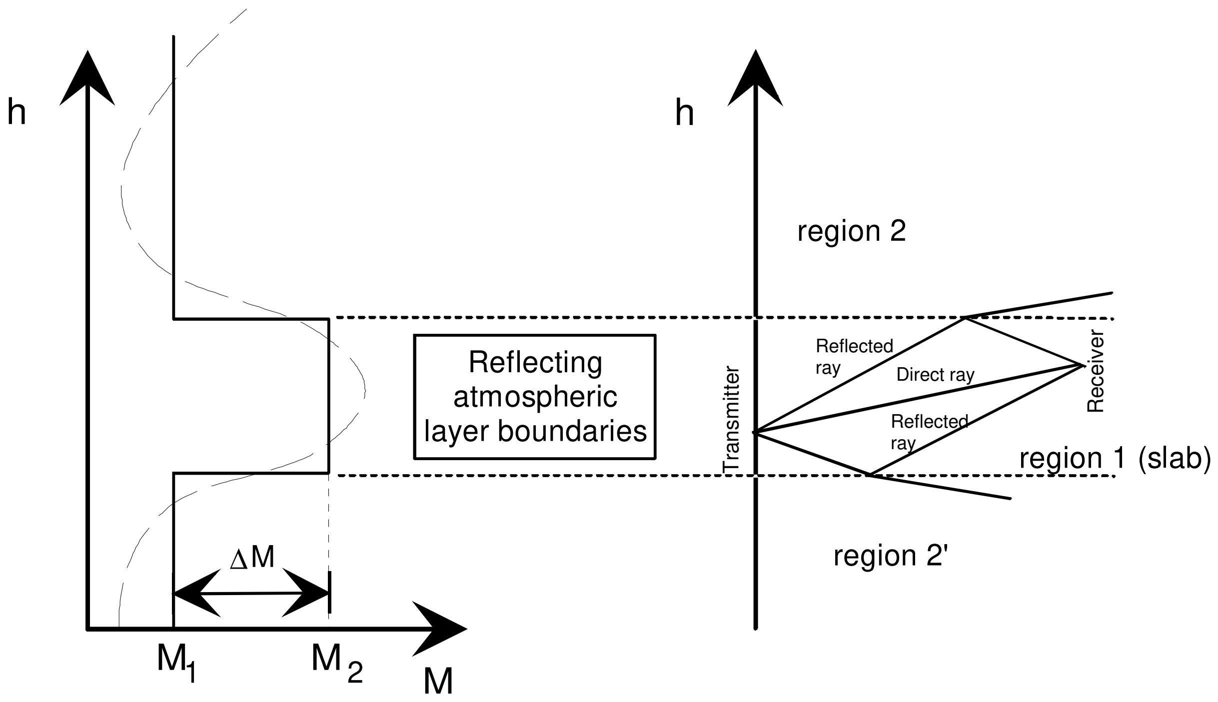
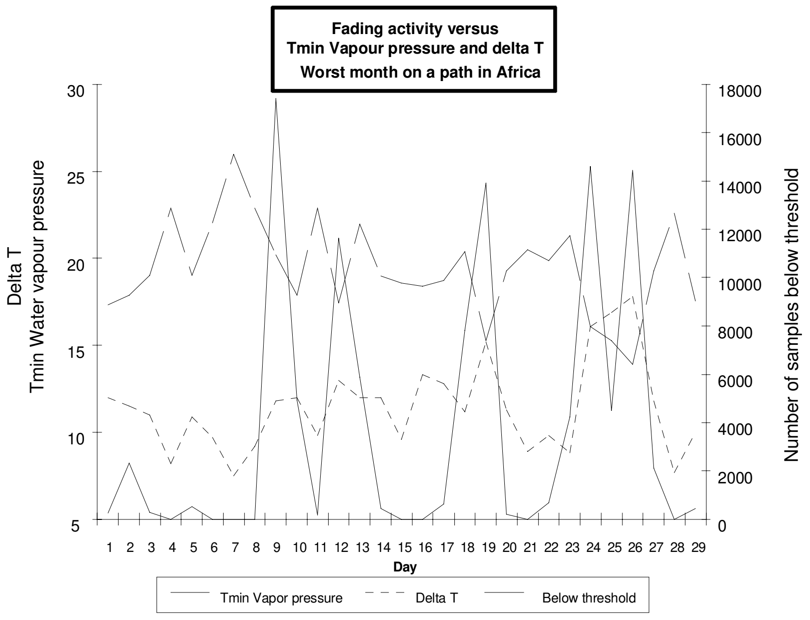


Figure 8 Elevated duct [47]

2.5.3 Formation of a duct



The resemblance between the fading activity and the nocturnal difference in temperature (delta T) and water vapour pressure is shown above. Large delta T means large fading activity. Little water vapour content means high fading activity. Both large difference in diurnal temperature and low water vapour content is closely connected to the probability of having an inversion layer that causes a radio duct.

During daytime the sun heats the ground giving convection and a well-mixed atmosphere. A calm night will give radiation from the warm ground, giving temperature inversion. This in turn gives a region near ground where $\frac{dM}{dh} < 0$, resulting in a ground based duct. Just after sunrise in the morning, the ground is heated by the sun again, and the convection starts near the ground. The ground based duct rises, resulting in an elevated duct as indicated in figure 9. [43]

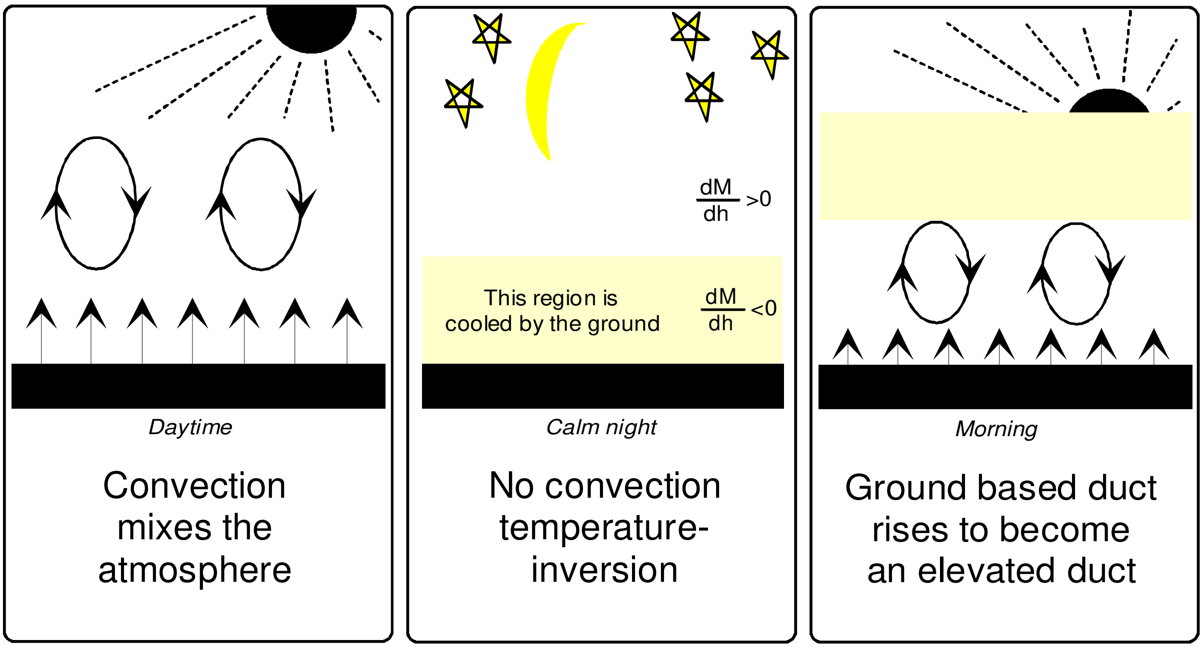


Figure 9 Formation of ducts

2.5.4 Ducting probability

Figure 10 shows the percentage of time when $\frac{dN}{dh}$ is less than -100 N units/km in May. This figure gives a good indication where it is most likely to experience ducting. One can read from the figure that the equatorial regions are most vulnerable to ducts. In temperate climate the probability of formation of ducts is less.

This difference in ducting probability can be explained by the difference in temperature and most of all by the difference in humidity.

The ducting probability follows seasonal variations. Figures showing ducting probabilities for different months are given in figures A1 through A4 in appendix A. [18]

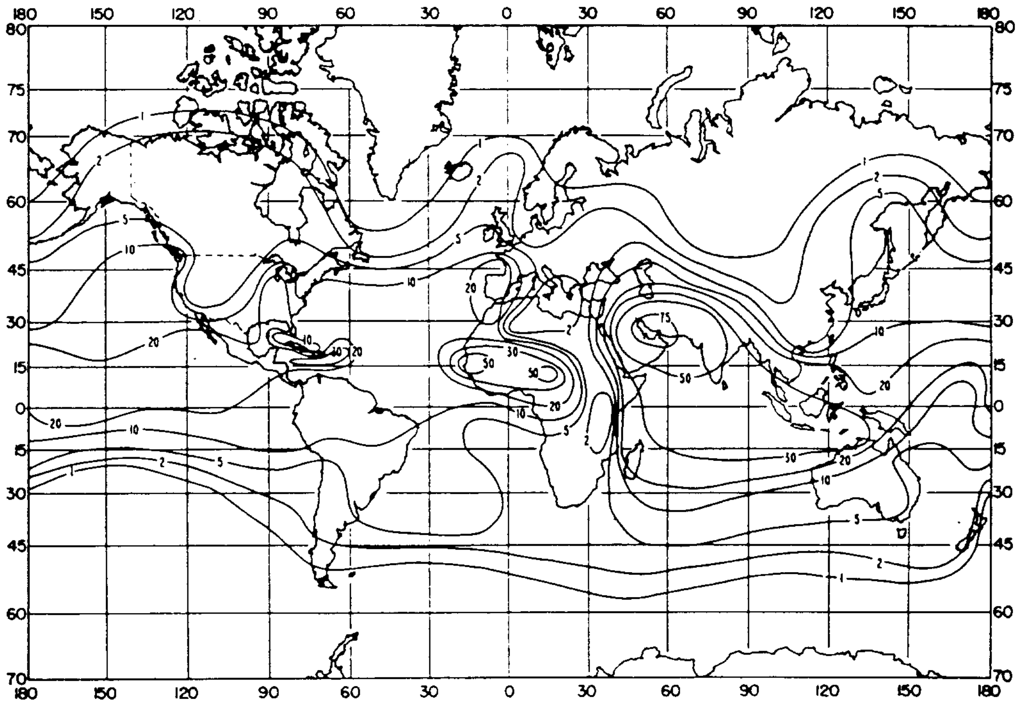
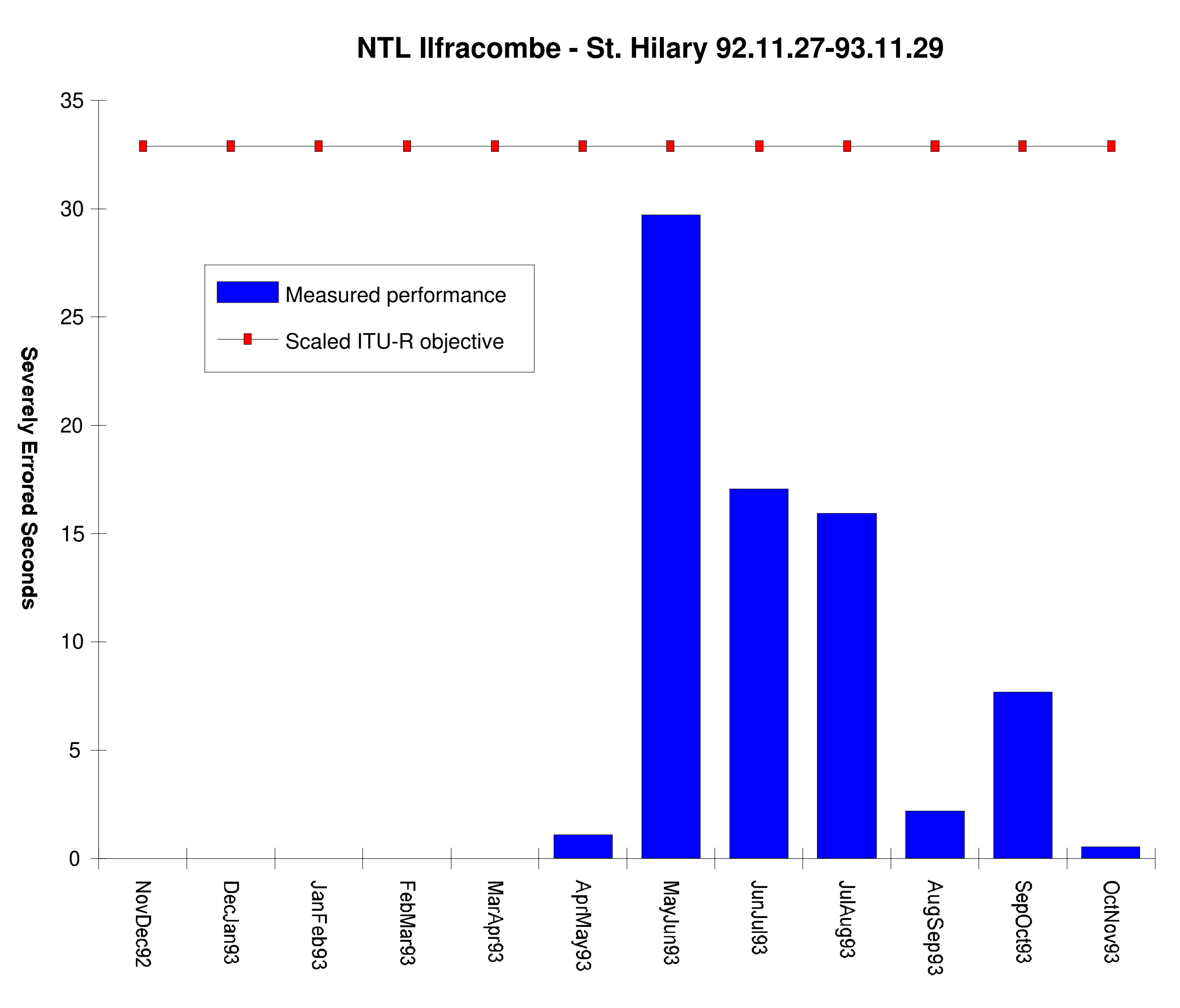


Figure 10 Ducting probability in May (ITU-R rep. 563-4 [28])

The Bristol channel path

The path Ilfracombe - St. Hilary will be used as an example path throughout this book. The path is 58.65 km long and 2/3 of the path is over sea water (crossing the Bristol channel in UK). The radio equipment is NL141 from Nera, a 34 Mbit/s radio operating at 7.5 GHz in a 2+0 configuration with space diversity. More details on the system will be introduced in the following chapters. The system is owned by NTL (National Transcommunications Ltd.).



The above chart clearly shows the seasonal variations of the ducting probability, expressed by the numbers of severely errored seconds logged over a measurement period of one year. The worst month is May-June, and the period May-August has the largest number of errors. This corresponds very well with the ITU-R P_L-contour maps in appendix A [28], where the months with the largest ducting probability are May and August for the South Wales area. [44]

Chapter 3

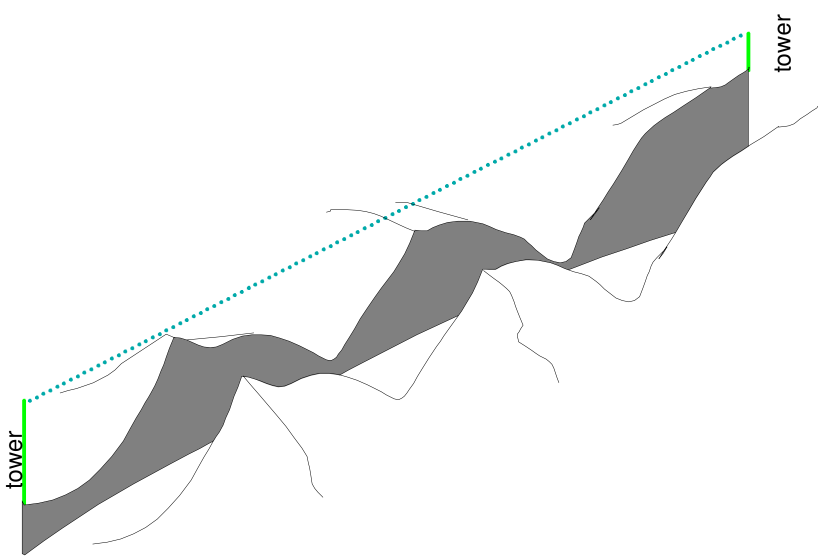
Terrain profiles

3.1 Introduction

Terrain profiles are necessary to determine site locations and antenna heights. Care must be taken to assure free sight between the sites and avoid reflections. Additional parameters concerning evaluation of radio sites are covered in chapter 4.

3.2 Path profiles

Starting with a vertical slice through a simplified three dimensional terrain sketch, the terrain profile in figure 11 could be drawn.



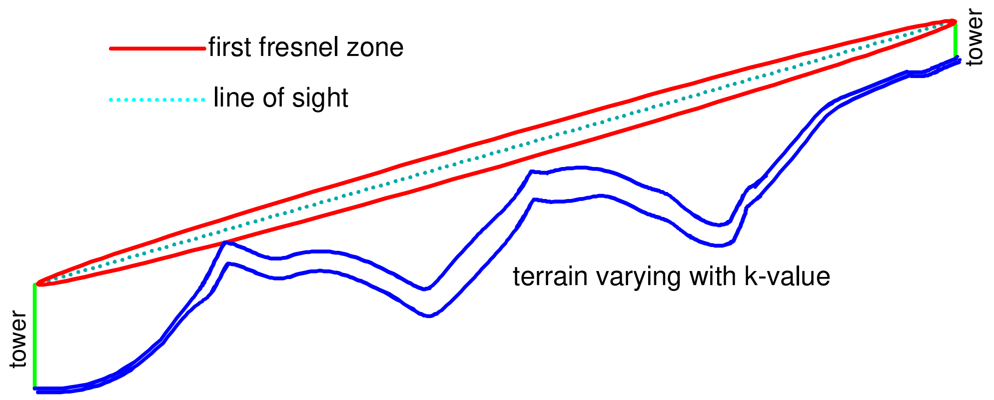
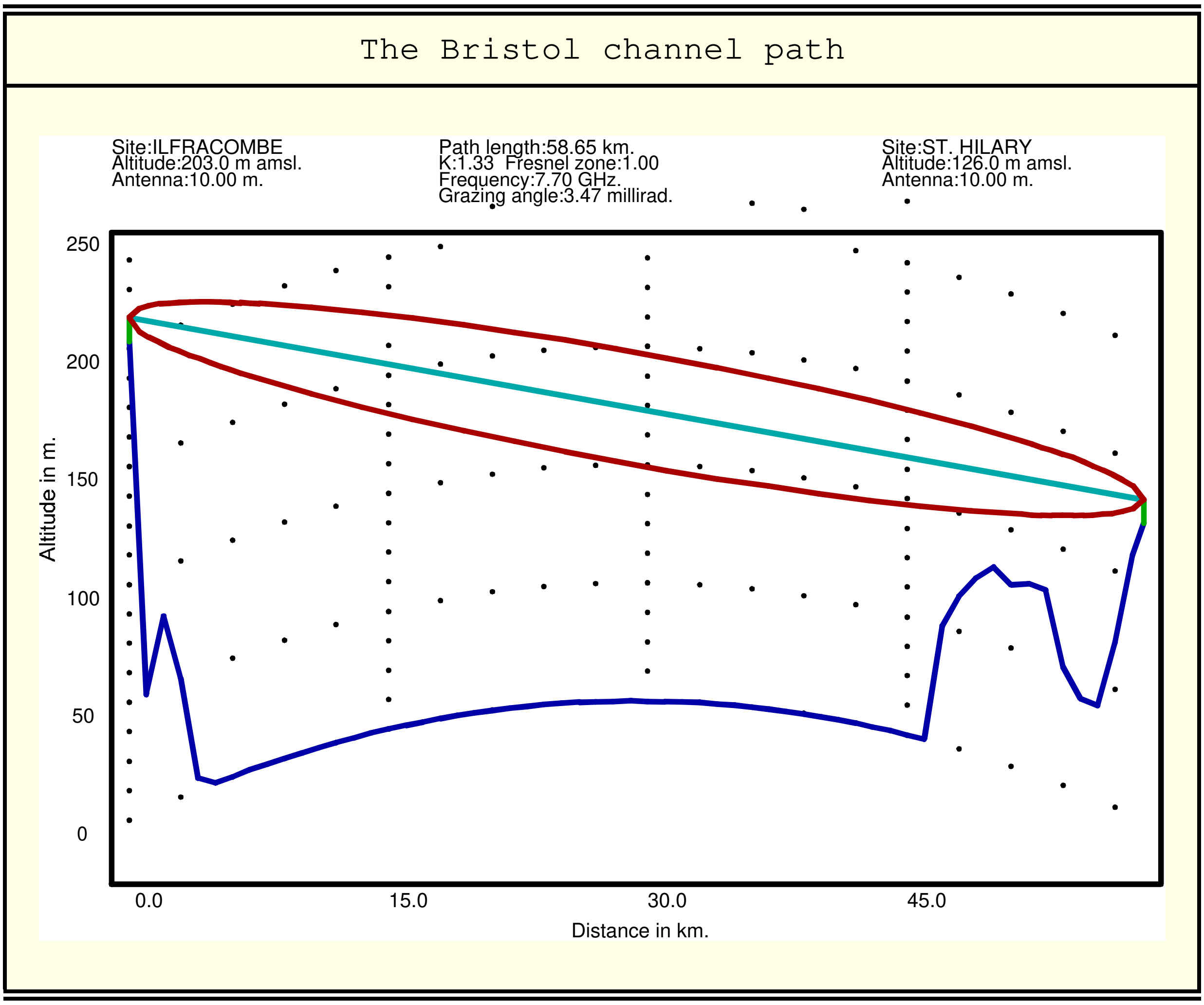


Figure 11 Typical path profile

Figure 11 shows the path profile with first Fresnel zone and terrain that varies with k-value. The line of sight is drawn as a straight line in figure 11, and the ray bending due to variations in k-value is added to the terrain heights. There must be clearance for first Fresnel zone to avoid diffraction loss in addition to the free space loss. The expected diffraction loss can be found using figure 12. [34]



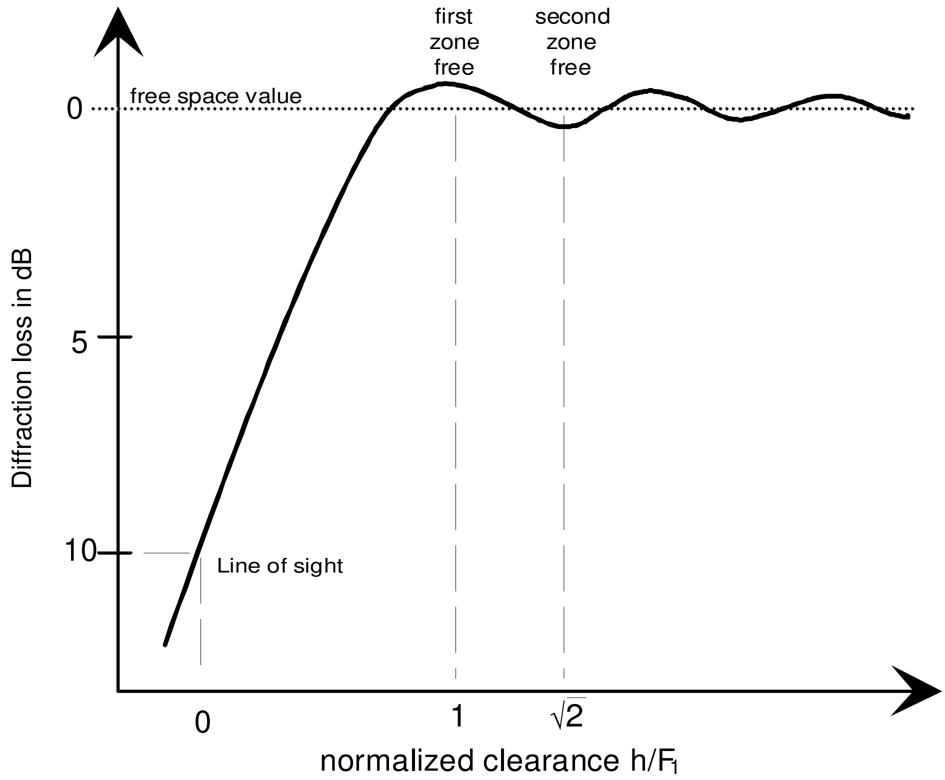


Figure 12 Additional loss due to diffraction

In the absence of a general procedure that would allow a predictable amount of diffraction loss for various small percentages of time (a statistical path clearance criterion), the following procedure is advised by the ITU-R [31]:

a) determine the antenna heights required for the appropriate median value of the point *k*-factor (in the absence of other data use k =4/3) and $1.0F_1$ clearance over the highest obstacle.

b) obtain the value of k_e (99.9%) from figure 13 for the path length in question.

c) calculate the antenna heights required for the value of k_e obtained from step b) and the following Fresnel zone clearance radii:

Temperate climate	*Tropical climate*
$0.0F_1$ if there is a single isolated path obstruction. $0.3F_1$ if the path obstruction is extended along a portion of the path.	$0.6F_1$ for path lengths greater than about 30 km

d) use the larger of the antenna heights obtained by steps a) and c).

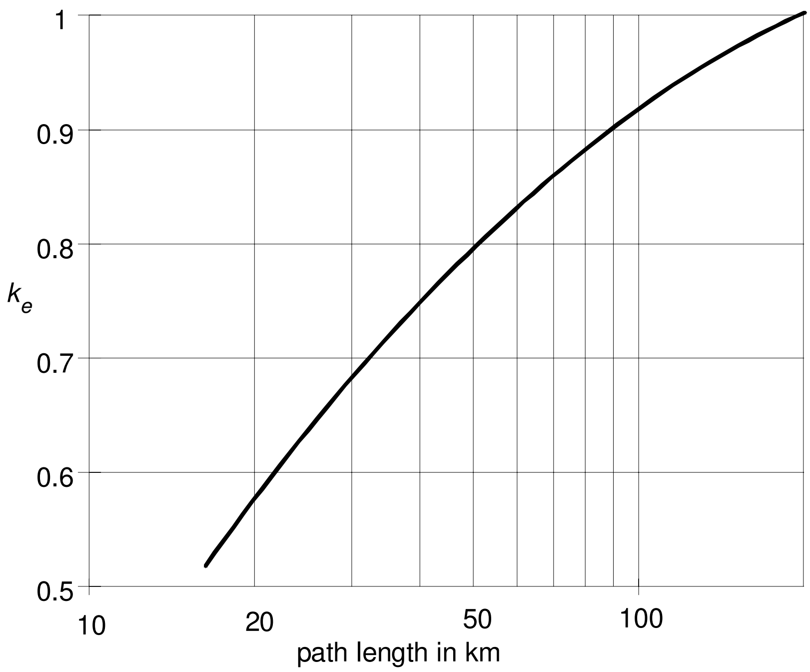
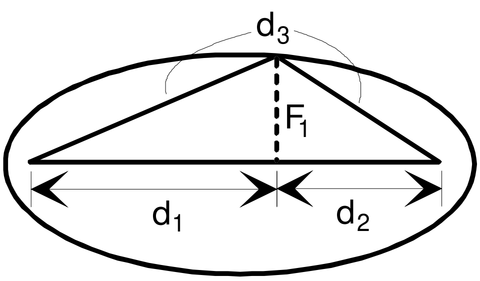


Figure 13 Value of k_e exceeded for approximately 99.9% of the worst month [31] (Continental temperate climate)

3.3 Fresnel zone

The first Fresnel zone is defined as the locus of points where $d_3 - (d_1 + d_2) = \lambda/2$. This equation describes an ellipse, but for practical applications the radius F_1 may be approximated by the formula



11) $$F_1 = 17.3\sqrt{\frac{d_1 \cdot d_2}{f \cdot d}} \quad [\mathrm{m}]$$

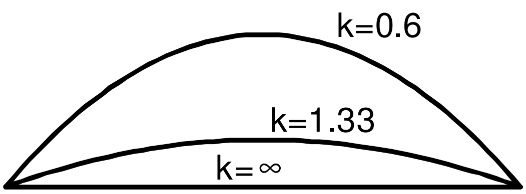
where f is the frequency in GHz

the total path distance $d = d_1 + d_2$ in km

3.4 Earth bulge

In order to draw the line of sight straight in a path profile, the ray bending due to variations in k-value is added to the terrain heights. The modification of the terrain heights is given by

12) $$\frac{d_1 \cdot d_2}{12.74 \cdot k} \quad [\mathrm{m}]$$



where k is the k-value

the other parameters have their previous definition.

3.5 Ground reflections

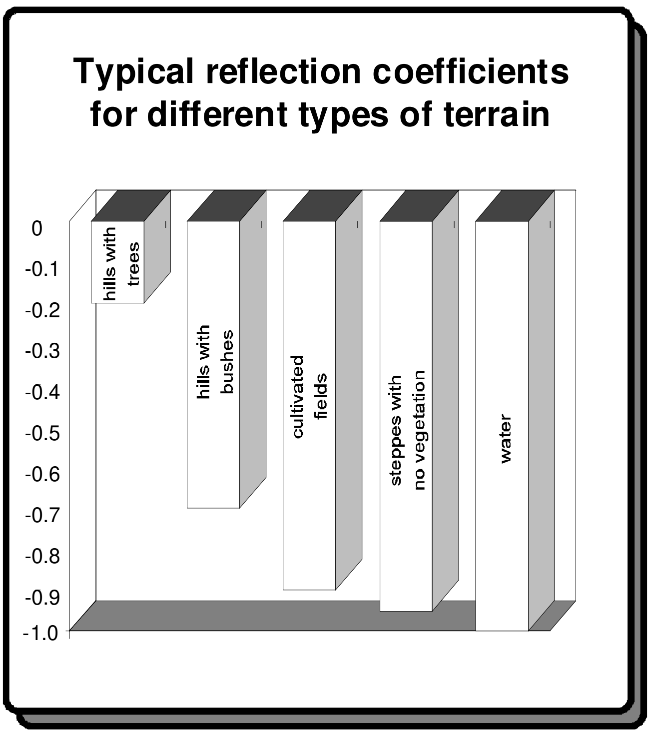


Figure 14 shows a typical signal reflection from the sea surface. The more conductive the ground is, the stronger the reflection will be. Reflections from sea, march, etc. are thus more critical than reflections from terrain with vegetation. The reflection coefficient for a given type of terrain is also frequency dependant. Generally, the reflection coefficient decreases with frequency. On the other hand, a larger area is required to reflect a signal at a lower frequency. The effective reflection coefficient is also a function of the path's grazing angle and the curvature of the Earth (the k-value). Generally vertical polarization gives reduced reflection, especially at lower frequencies. [34]

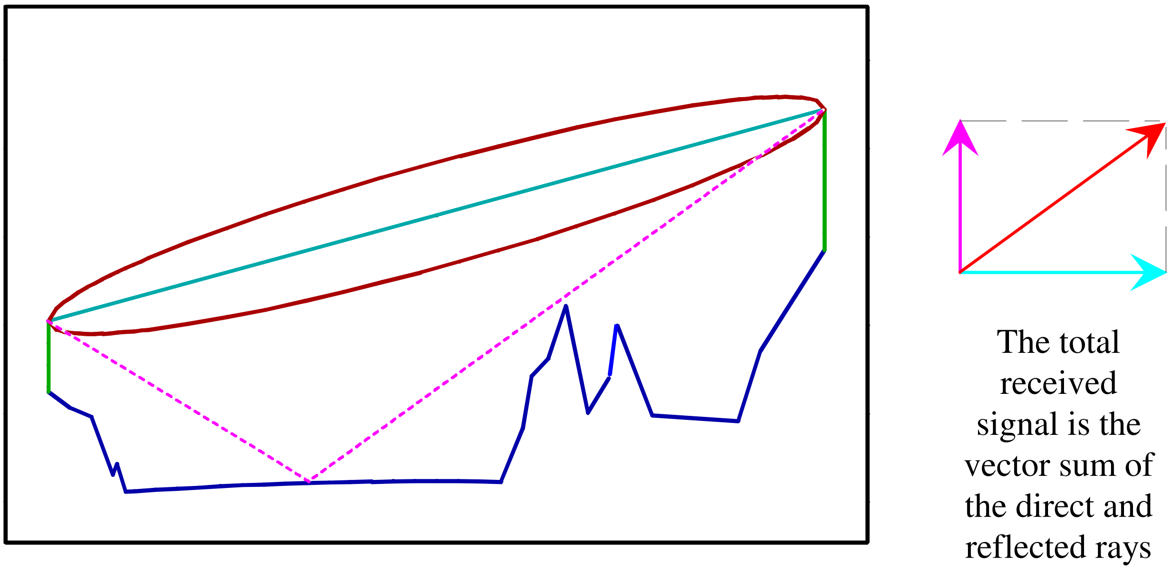
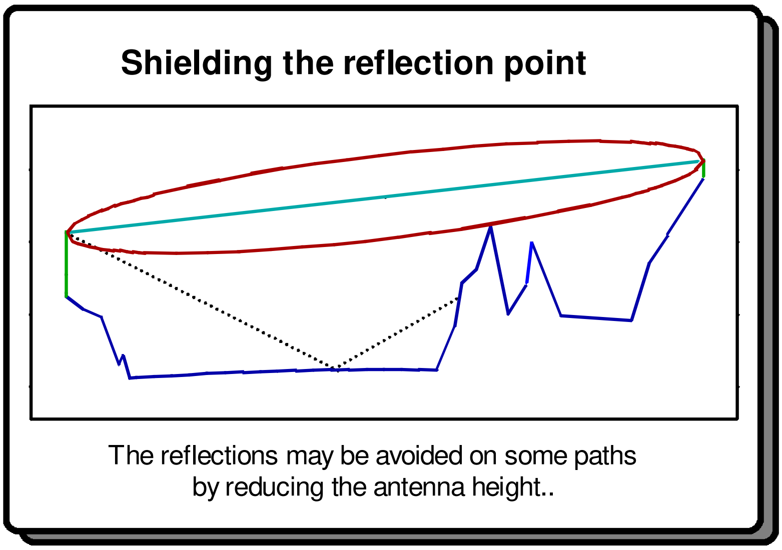


Figure 14 Ground reflections

As indicated in figure 14 the received signal is the sum of the direct and the reflected signal. Adding these two signals will give a signal strength that is a function of the height at the receiver site as indicated in figure 15. To counteract the effect of ground reflections, space diversity arrangements with two receiver antennas with a vertical separation are widely used. The antenna separation should give maximum received signal level at the space antenna when the main antenna is at a minimum, and vice versa.



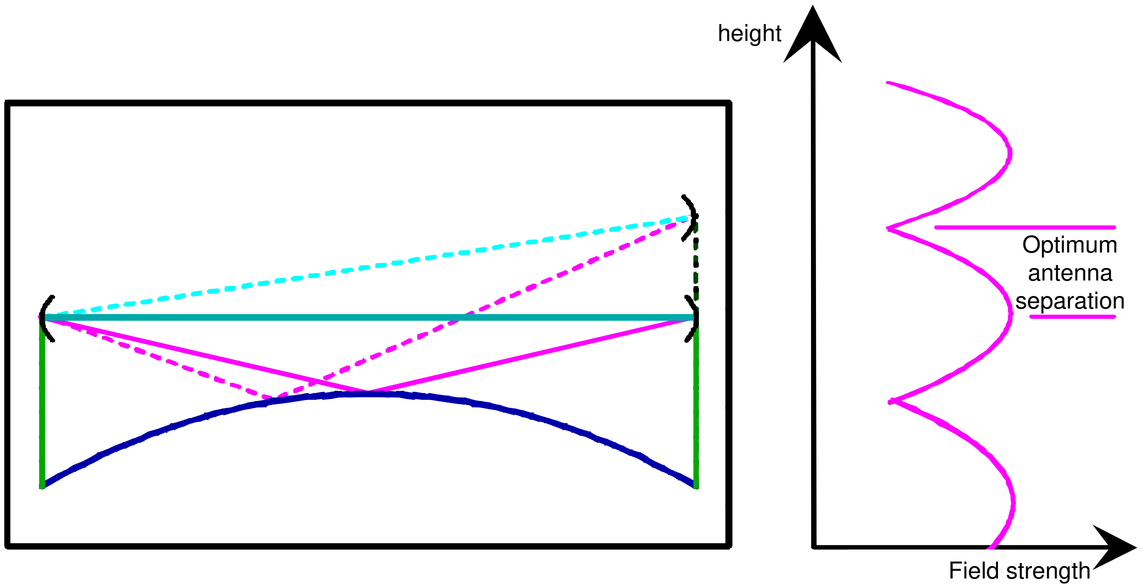


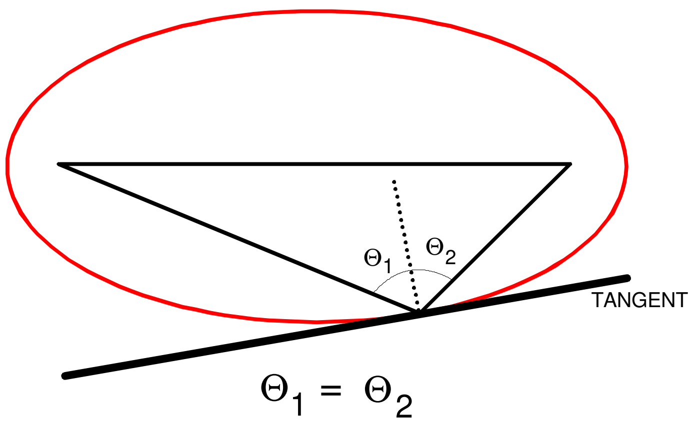
Figure 15 Optimum antenna separation by space diversity

This optimum antenna separation may be found using one of two different methods.

1. Geometrical method using Fresnel zones.

2. Analytical method using series expansions.

3.5.1 Geometrical method



A geometrical property of the ellipse is that the angle of incidence equals the reflection angle at the circumference. This property may be used to find the reflection point. When the terrain equals the tangent to the ellipse, a reflection point has been found. Consequently the reflection point may be found by increasing the Fresnel zone until it touches the terrain. If the ellipse tangent is parallel to the terrain, there is a reflection point. (See figure 16)

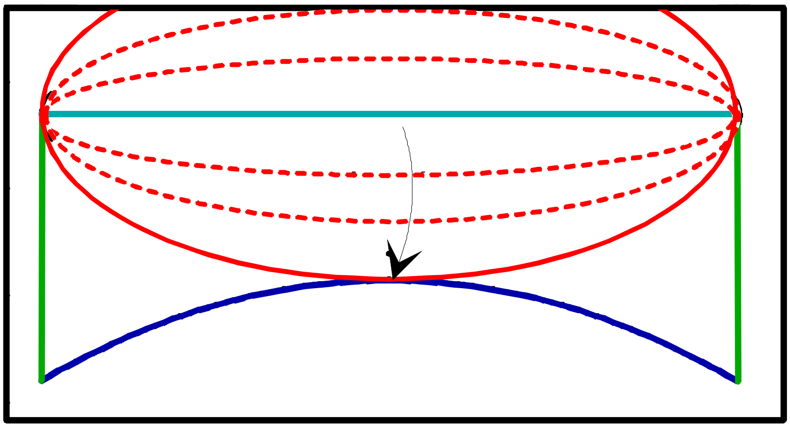


Figure 16 Finding reflection point graphically

The optimum antenna separation may also be found graphically. When the reflection point has been found using figure 16, increase or decrease the Fresnel zone with half a wavelength. Place this new ellipse upon the terrain as shown in figure 17, and read the variation in antenna height. The difference between the antenna height for the two Fresnel zones drawn in figure 17 corresponds to the optimum vertical antenna separation for a space diversity arrangement.

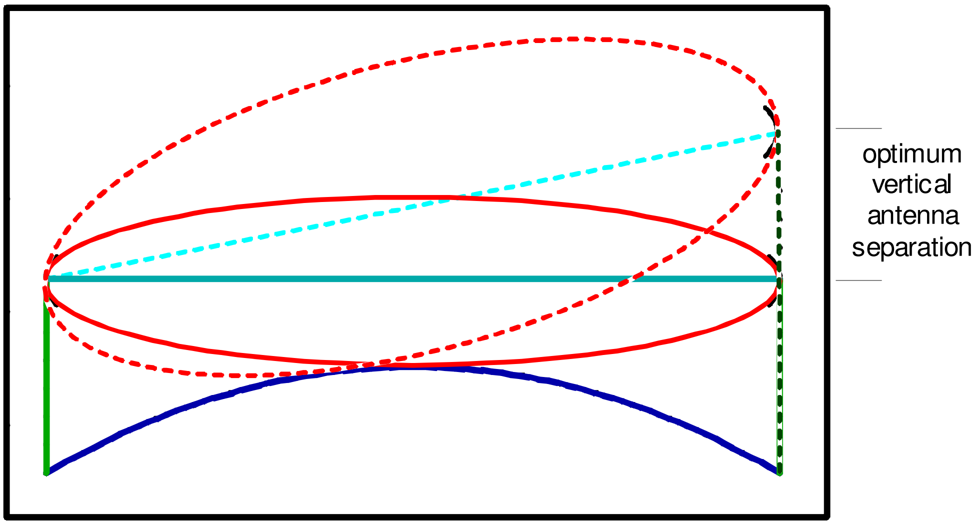


Figure 17 Optimum antenna separation (graphical method).

3.5.2 Analytical method

The location of the reflection point may be found by using the formulas given below [34].

13) $$q = \frac{h_1 - h_2}{h_1 + h_2}$$

q … parameter to be used in formulas

h_1 … height of antenna above reflection point at site A in m

h_2 … height of antenna above reflection point at site B in m

14) $$Q = \frac{k \cdot 51(h_1 + h_2)}{2 \cdot d^2}$$

Q … parameter to be used in formulas

k … effective Earth radius factor (k - value)

d … total path length in km

15) $$V = \frac{q}{1 + \frac{1}{Q}}$$

V … parameter to be used in formulas

16) $$Z = V \cdot \sum_{i=0}^{\infty} \frac{V^{2i}}{(1+Q)^i}$$

Since 16) converges quite rapidly, it can be terminated after the fourth term with good approximation:

17) $$Z \approx V\left(1 + \frac{V^2}{1+Q} + 3\frac{V^4}{(1+Q)^2} + 12\frac{V^6}{(1+Q)^3}\right)$$

18) $$d_1 = \frac{d}{2}(1+Z)$$

19) $$d_2 = \frac{d}{2}(1-Z) = d - d_1$$

d_1 … distance from site A to reflection point in km

d_2 … distance from site B to reflection point in km

The difference in path length for the direct and the reflected signal expressed in meters 20) and in wavelengths 21) is given by:

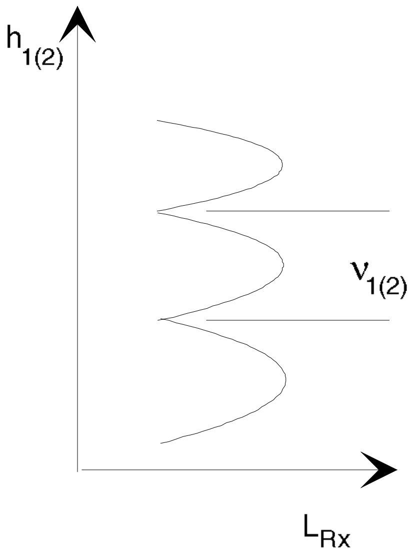
20) $$\delta = \frac{2}{d}\left(h_1 - \frac{d_1^2}{12.74 \cdot k}\right)\left(h_2 - \frac{d_2^2}{12.74 \cdot k}\right) \cdot 10^{-3}$$

21) $$\tau = \frac{\delta \cdot f}{0.3}$$

The pitch distance (indicated in figure 15) is given by:

22) $$\upsilon_1 = \frac{0.3 \cdot d}{2 \cdot f} \cdot \frac{1}{h_2 - \dfrac{d_2^2}{12.74 \cdot k}} \cdot 10^3$$

23) $$\upsilon_2 = \frac{0.3 \cdot d}{2 \cdot f} \cdot \frac{1}{h_1 - \dfrac{d_1^2}{12.74 \cdot k}} \cdot 10^3$$



The optimum antenna separation is thus half of the pitch distance:

24) $$\Delta h_{1(2)} = \frac{\upsilon_{1(2)}}{2}$$

Chapter 4

Field survey

During the planning stage for a digital microwave system it will be required to do a field survey.

The objectives of a field survey can be the following :

- *Verify exact site location*
- *Verify line-of-sight*
- *Classify path type*
- *Confirm space in existing stations*
- *Check propagation conditions*
- *Check frequency interference possibilities*
- *Check soil conditions for new towers*
- *Check site access and infrastructure in the area*

4.1 Survey Procedures

4.1.1 Preparations

In order to reduce the field work, careful preparations should be made. A detailed map study is always a good start. After having located all the sites (including alternative locations), preparation of path profiles should be done.

Maps to a scale of 1 : 50 000 (or more detailed) should be used to draw a terrain profile of the microwave path. Critical obstacles should be marked in order to verify line-of-sight in the field and possible reflection points should also be noted in order to check in the field.

Preliminary antenna heights may be determined at this stage. Organising of transport to and accommodation in remote areas is also important to do as early as possible.

Information about other microwave link operators in the area can be important if frequency interference measurements shall be performed.

4.1.2 Field Work

The following activities are typical for planning of new microwave systems and sites :

- *Verification of site positions and altitudes.*

This is done today in most cases by using a GPS (Global Positioning System). Theodolite for land surveying can also be used for more accurate positions, but this is very time consuming.

The standard GPS today will have an accuracy of 30 - 100 m depending on the quality of the signals. If required, differential GPS can be used and will give more accurate co-ordinates. However, more expensive equipment is required and the process is much more complicated and time consuming. The altitude can be determined from the map, or by using an altimeter or by using a theodolite.

- *Confirmation of line-of-sight*

If critical obstructions are seen on the path profiles, they should be checked more accurately. This is very often done by using a mirror for a line-of-sight test. This is very easy to do and the flash from a mirror in sunlight can be seen from very long distances in clear weather conditions. (More than 100 km in good conditions.)

For shorter paths several other methods may be used. Balloons may be used to verify the required tower height if there is no line-of-sight from ground level. Strong lamps or powerful flash-lights may also be used, particularly in the dusk.

Another possibility is field strength measurements that can verify if the path has line-of-sight or the signal is obstructed. High frequency bands will be very much affected if there is no line-of-sight. A combination of high frequency and lower frequency may give a good indication to the real obstruction of the path.

In some cases altimeters are used to check obstructions or the terrain between the sites. They can be used for flat areas with no existing towers, for example.

- *Path classification*

The prediction model for system performance uses different path classifications to improve the accuracy of the prediction model. In order to get the best prediction, correct path classification should be performed. The following classes are used:

Overland paths:

Plain terrain / low altitude (0 - 400m)
Hilly terrain / low altitude (0 - 400m)
Plain terrain / medium altitude (400 - 700m)
Hilly terrain / medium altitude (400 - 700m)
Plain terrain / high altitude (>700m)
Hilly terrain / high altitude (>700m)
Mountainous terrain / high altitude (>700m)

The altitude refers to the altitude of the lower of the two antennas.

Coastal links or over water paths:

Paths near/over large bodies of water
Paths near/over medium-sized bodies of water

See chapter 9.2.1.2 New prediction method (page 71) for further details.

- *Propagation conditions*

The propagation conditions are depending on the atmospheric conditions in the area as well as the path.

In addition to the path classification, interesting observations of the terrain should be noted. Areas of flat swampy terrain like rice fields or other obviously reflecting surfaces should be located exactly so the possibility of harmful reflections can be calculated and possibly avoided. Desert areas or paths running parallel to the coastline should be noted, certainly in flat, warm areas. See chapter 9.2.1.2 New prediction method) for examples of path classifications and considerations related to performance predictions.

- *Frequency interference probabilities*

The possibility of frequency interference can be checked by using an antenna horn, a low noise amplifier and a spectrum analyser. Existing microwave signals in the relevant frequency band can be picked up, and based on signal strength and direction it is possible to calculate the interference levels.

If there is no existing station or towers that can be used for these measurements, provisional power and/or towers may have to be arranged for these purposes in important cases.

- *Soil investigations*

It may be required to do soil tests to find out the nature of the soil for the tower foundations. This is important in cases where there might be clay or very high water levels, as piling of the foundations may be required. Also in rocky terrain the nature of the soil is important.

- *Infrastructure in the area*

The presence of commercial power in the area is important for new stations. The distance to power lines is checked. Distance to site from roads and the possibility of constructing access roads are also checked.

In the case of modification or expansion of existing systems the field survey has some additional points which are important to check. Normally a checklist is used, and a site layout drawing is made:

Type of building: Concrete, wood, prefabricated shelter.
Material used in ceiling, walls, and floor.
Measurements of rooms, height of ceiling.
Space for new equipment in the equipment room.
How to fix waveguide and cables to walls, ceiling.
Waveguide outlets through wall, etc.
New air dryer for waveguides required?
Available power (AC - DC).
Existing battery capacity. Are new batteries necessary?
Can existing tower be used?
Distance from building to tower.
How to install the waveguide safely outside.
Space for new antenna at the correct height in the tower.
Check grounding system for the tower and the station.
Possible interface problems with existing equipment.
Possible interference problems with existing equipment.

4.2 Survey Equipment

The following survey equipment is typical for a microwave survey and may always be used or in some cases.

Maps in scale 1 : 50 000 or better
Camera, digital camera is used occasionally
Binoculars
Compass
Altimeters
Thermometer
Signalling mirrors
Hand-held radio communication equipment
Tape measure
Satellite navigation equipment (GPS)
Theodolite
Antenna horns
Low noise amplifier
Spectrum analyser
Portable personal computer
Walkie-talkie or cellular phone (verify coverage)

4.3 Survey Report

After completion of the field survey a survey report will normally be prepared.

This report can include the following :
- *System description*
- *Site description and layout*
- *Antenna and tower heights*
- *Path profiles*
- *System performance calculations*
- *Frequency plans*
- *Photographs*

4.4 Difficult areas for microwave links

Some areas are more difficult for microwave links than others, and the reasons can be atmospheric conditions or path dependent.

- *Over water paths*

Always difficult due to sea reflections with a high reflection coefficient. Ducting probability is also high. Reflections may be avoided by selecting sites that are shielded from the reflected rays.

- *Swamp and rice fields*

May cause strong ground reflections. The probability for multipath fading is high. The propagation conditions may look different at different times of the year. Critical period is the rainy season(monsoon).

- *Desert areas*

May cause ground reflections, but sand does not have a high reflection coefficient. The most critical is the high possibility of multipath fading and ducting due to large temperature variations and temperature inversions.

- *Hot and humid coastal areas*

High ducting probability.

Chapter

5

Performance and availability objectives

5.1 Introduction

The error performance and the availability objectives for different microwave systems are based on the definition of the network.

These objectives are recommended by ITU-T and ITU-R, the background information found in ITU-T Recommendations. G.801 [1], G.821 [2] and G.826 [3].

The objectives in G.821 are requirements for Integrated Services Digital Networks (ISDN) and are related to each direction of a 64 kbit/s channel. When measuring on higher bit rates, the performance can be estimated according to ITU-T Rec. G.821, Annex D. The formulas are provisional, and will be substituted by G.826.

5.1.1 Summary of ITU objectives

A short summary of ITU objectives for radio-relay systems is given in table 1.

G.821	G.826
~ High grade	~ International portion – Terminating country – Intermediate country
~ Medium grade – Class 1 – Class 2 – Class 3 – Class 4	~ National portion – Long haul section – Short haul section – Access section
~ Local grade	

Table 1 Summary of ITU objectives

5.2 Objectives based on ITU-T G.821

5.2.1 Performance objectives

5.2.1.1 Some definitions

The ITU recommendations contain a number of definitions and abbreviations that need to be defined. See also appendix E (page 186) for a complete list of abbreviations used in this book.

ISDN - *Integrated Services Digital Network*

All voice, data and other services shall be able to use this network.

HRX - *Hypothetical Reference Connection*

This is a model for a long international connection, 27500 km. See Figure 18. It does not represent the worst case but is supposed to include the majority of real situations. The HRX includes transmission systems, multiplexing equipment and switching.

HRDL - *Hypothetical Reference Digital Link*

This is the same as:

HRDP - *Hypothetical Reference Digital Path*

The HRDL is mainly for line systems and the HRDP is for radio relay systems.

The HRDP for high grade digital radio relay systems is 2500 km and does not include switching equipment. To define performance objectives for real links, the HRDP is split up in smaller sections. See Figure 18.

HRDS - *Hypothetical Reference Digital Section*

The HRDS shall represent section lengths likely to be encountered in real networks. The model does not include other digital equipment, such as multiplexers/demultiplexers. The length of a HRDS is at the moment defined as being 280 km or 50 km and may have different performance classifications. See Figure 18.

SES - *Severely errored second*

A bit error ratio (BER) of 10^{-3} is measured with an integration time of one second. BER of 10^{-3} is the point where the signal is unacceptable to most services.

DM - *Degraded minutes*

A BER of 10^{-6} is measured with an integration time of one minute.

ES - *Errored second*

An ES is a second that contains at least one error. ES may result from causes other than fading.

RBER - *Residual bit error ratio*

The RBER on a system is found by taking BER measurements for one month using a 15 min integration time, discarding the 50% of 15 min intervals which contain the worst BER measurements, and taking the worst of the remaining measurements. The method is provisional.

5.2.1.2 Objectives

The performance objectives are separated from availability objectives. The system is considered unavailable when the BER is higher than 10^{-3} for 10 consecutive seconds or more. This period of time should be excluded when the performance of the system is studied.

The performance objectives for real digital links are divided into separate grades. See figure 18. Those are "high grade" , "medium grade" and "local grade". The allocation to the high grade objective is considered to be proportional with distance between 2500 km and 280 km, while medium grade and local grade are considered block allowances. The Administration in the country concerned should decide which grade to be used for planning objectives.

The performance objectives for an HRX are described in ITU-T Rec. G.821. [2]

SES - BER should not exceed 10^{-3} for more than 0.2% of one-second intervals in any month.

DM - BER should not exceed 10^{-6} for more than 10% of one-minute intervals in any month.

ES - Less than 8% of one-second intervals should have errors.

SES

The total allocation of 0.2% is divided as follows:

0.1% is divided between the three classifications

Classification	Objectives
High grade	0.04%
Medium grade	0.015% block allowance to each end
Local grade	0.015% block allowance to each end

The total is then 0.04% + 2 x 0.015% + 2 x 0.015% = 0.1%. See figure 18.

The remaining 0.1% is a block allowance to the high grade and the medium grade portions. That is 0.05% to each of a 2500 km HRDP.

DM

The allocations of the 10% to the three classifications are as shown in ITU-T Rec. G.821, Annex C [2].

High grade	Medium grade	Local grade
4.0%	2 x 1.5%	2 x 1.5%

ES

The allocations of the 8% to the three classifications are as shown in ITU-T Rec. G.821, Annex C [2].

High grade	Medium grade	Local grade
3.2%	2 x 1.2%	2 x 1.2%

5.2.2 Availability objectives

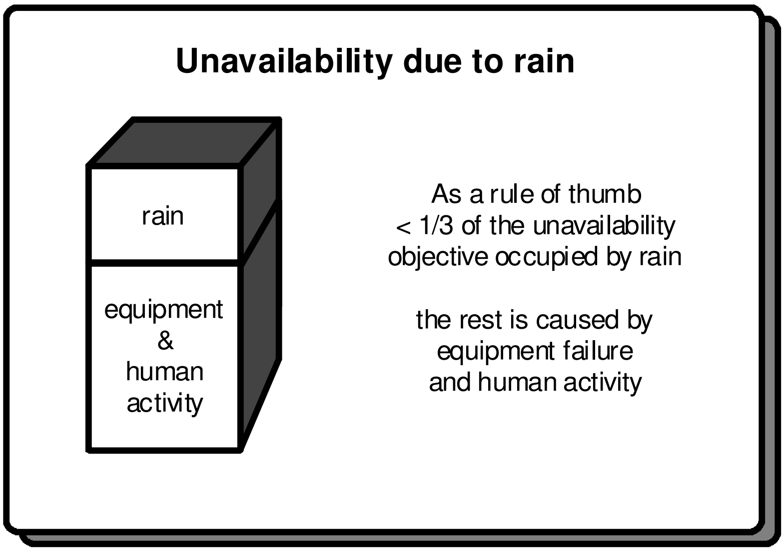
The ITU-T has not established any availability objectives for an HRX.

Availability objectives for an HRDP can be found in ITU-R Rec. 557. [5]

An HRDP is defined unavailable when one or both of the following conditions occur for more than 10 consecutive seconds:

- the digital signal is interrupted.

- the BER in each second is worse than 10^{-3}.



Unavailability of multiplex equipment is excluded. ITU-T will establish objectives for these types of equipment. The unavailability objective should be divided into one portion for equipment effects and one portion for propagation effects. The size of the two portions is more or less up to the different administrations or route designers, but a number of administrations are using 30% - 50% for outage due to rain.

The availability objective for a 2500 km HRDP should be 99.7% of the time, the percentage being considered over a sufficiently long time. The period is probably for more than one year, but the time is under study. The unavailability objective is then 0.3%.

5.2.3 Circuit classification

The objectives for the different circuit classifications are presented as performance and availability objectives for "High grade", "Medium grade" and "Local grade" circuits.

5.2.3.1 High grade circuits

The 0.04% for SES is scaled down to 0.004% for a 2500 km HRDP. In addition there was given an allowance of 0.05% for the HRDP to take care of adverse propagation conditions.

The objective for SES will then be: 0.05% + 0.004% = 0.054%

The 4.0% for DM is scaled down to 0.4% for a 2500 km HRDP.

The 3.2% for ES is scaled down to 0.32% for a 2500 km HRDP.

The ITU-R objectives for real circuits describe system lengths between 280 km and 2500 km. See ITU-R Rec. 594 [6] and ITU-R Rec. 695 [27]. They are based on the HRDP, and the objectives are scaled down to a minimum of 280 km. See ITU-R Rec. 634 [24]. Performance objectives for shorter distance than 280 km are still under study.

The objectives are:

SES BER>10^{-3} for no more than (L/2500)·0.054% of any month, integration time 1 s.

DM BER>10^{-6} for no more than (L/2500)·0.4% of any month, integration time 1 min.

ES Errored seconds for no more than (L/2500)·0.32% of any month.

RBER RBER< ($L \cdot 5 \cdot 10^{-9}$)/2500

Availability A = 100 - (0.3·L/2500) %

When DM is calculated, the seconds when BER>10^{-3} (SES) should be excluded.

The Bristol channel path

The down-scaled objectives for the 58.65 km long path Ilfracombe - St. Hilary are:

SES - 0.001267 % ; 33 seconds in worst month.

DM - 0.009384 % - 0.001267 % = 0.008117 % ; 3.5 minutes in worst month.

ES - 0.007507 % ; 195 seconds in worst month.

RBER - $1.2 \cdot 10^{-10}$

A - 99.993 % ; unavailable less than 36 minutes a year

5.2.3.2 Medium grade circuits

Medium grade objectives are supposed to be used for national networks, normally between the local exchange and the international switching centre. However , this depends very much on the size of the country and the size of the networks in the country.

According to ITU-T Rec. G.821 [2] the local grade and medium grade portions are permitted to cover up to the first 1250 km of the circuit from the T - reference point [7] extending into the network. Since the length of the local grade portion is usually negligible, the maximum length of the medium grade portion is approximately 1250 km.

The medium grade portion has 4 quality classifications. See table in figure 18. Class 1 corresponds to high grade classification but can also be used for medium grade classification. The other three apply to medium grade only. The medium grade objectives for a total medium grade portion at each end of an HRX can be found in ITU-R Rec. 696 [8]. Comments are found in ITU-R Report 1052 [9].

For SES the objective was 0.015% with an additional allowance of 0.05%. That is 0.025% for each side. The total is 0.04%

For DM and ES there are no additional allowances. The objectives are:

BER not to exceed 10^{-3} for more than 0.04% of any month with integration time of 1 s.

BER not to exceed 10^{-6} for more than 1.5% of any month with an integration time of 1 min.

The total errored seconds should not exceed 1.2% of any month.

For an HRDS the ITU-R Rec. 696 [8] has made a table for the different classifications and objectives. These figures shall be used for lengths less than these distances.

Performance parameter	*Percentage of any month*			
	Class 1 280 km	**Class 2** 280 km	**Class 3** 50 km	**Class 4** 50 km
BER>10^{-3}	0.006	0.0075	0.002	0.005
BER>10^{-6}	0.045	0.2	0.2	0.5
Errored seconds	0.036	0.16	0.16	0.4
RBER	5.6 x 10^{-10}	Under study	Under study	Under study
Unavailability	0.033	0.05	0.05	0.1

If a system is a mixture of different classifications it must be ensured that the overall objective for the medium grade portion is not exceeded.

5.2.3.3 Local grade circuits

The local grade portion of the HRX represents the part between the subscriber and the local exchange. This may be a point-to-point or point-to-multipoint system, often of simple and cost-effective design.

The error performance objectives for the local grade portion can be found in ITU-R Rec. 697 [10] and comments in ITU-R Report 1053 [11].

Unavailability objectives for local grade circuits have not yet been established by the ITU-T or the ITU-R. The objectives for performance are as follows :

BER should not exceed 10^{-3} for more than 0.015% of any month with an integration time of 1 s.

BER should not exceed 10^{-6} for more than 1.5% of any month with an integration time of 1 min.

The total errored seconds should not exceed 1.2% of any month.

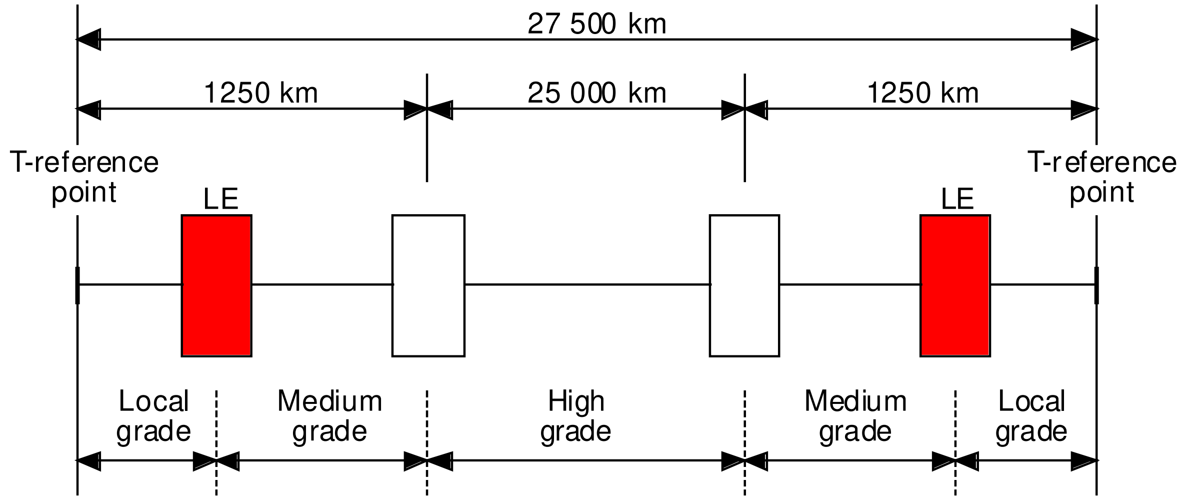


Figure 18 Hypothetical reference path, apportionment methodology G.821

5.6 Objectives based on G.826 and G.827

The ITU-T recommendation G.826 [3] specifies error performance parameters and objectives for international digital paths at or above the primary rate. These paths may be based on PDH, SDH or some other transport network. Future radio-relay systems, which will form part of these paths, have to comply with this recommendation. Generally G.826 specifies more stringent performance objectives than G.821 [2] does.

The ITU-T recommendation G.827 [4] specifies availability parameters and objectives for international digital paths at or above the primary rate. The 1996 version of this recommendation specifies no availability figures, only definitions. All parameters are still under study, and consequently no figures can be included in this textbook.

5.6.1 Performance objectives

5.6.1.1 Some definitions

The main difference between G.826 and G.821 is that G.826 uses *blocks* instead of *bits* as in G.821. Consequently the following definitions are based on block errors rather than bit errors.

Block	A block is a set of consecutive bits associated with the path; each bit belongs to one and only one block. An errored block (EB) is a block in which one or more bits associated with the block are in error.
Errored **B**lock	A block in which one or more bits are in error.
Errored **S**econd	A one-second period with one or more errored blocks. SES defined below is a subset of ES.
Severely **E**rrored **S**econd	A one-second period which contains ≥ 30% errored blocks or at least one Severely Disturbed Period (SDP)
Background **B**lock **E**rror	An errored block not occurring as part of a SES.

5.6.1.2 Parameters

Errored **S**econd **R**atio	The ratio of ES to total seconds in available time during a fixed measurement interval.
Severely **E**rrored **S**econd **R**atio	The ratio of SES to total seconds in available time during a fixed measurement interval.
Background **B**lock **E**rror **R**atio	The ratio of errored blocks to total blocks during a fixed measurement interval, excluding all blocks during SES and unavailable time.

5.6.1.3 Performance objectives

Rate Mb/s	1.5 to 5	>5 to 15	>15 to 55	>55 to 160	>160 to 3500
Bits/block	800-5000	2000-8000	4000-20 000	6000-20 000	15 000-30 000 *Note 2*
ESR	0.04	0.05	0.075	0.16	*Note 3*
SESR	0.002	0.002	0.002	0.002	0.002
BBER	$2 \cdot 10^{-4}$ *Note 1*	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	10^{-4}

Note 1 For systems designed prior to 1996, the BBER objective is $3 \cdot 10^{-4}$.

Note 2 Because bit error ratios are not expected to decrease dramatically as the bit rates of transmission systems increase, the block sizes (in bits) used in evaluating very high bit rate paths should remain within the range 15000 to 30000 bits/block. Preserving a constant block size for very high bit rate paths results in relatively constant BBER and SESR objectives for these paths.

As currently defined, VC-4-4c (Recommendation G.709) is a 601 Mbit/s path with a block size of 75168 Bits/block. Since this exceeds the maximum recommended block size for a path of this rate, VC-4-4c paths should not be estimated in service using this table. The BBER objective for VC-4-4c using the 75168 bit block size is taken to be $4 \cdot 10^{-4}$. There are currently no paths defined for bit rates greater than VC-4-4c (>601 Mbit/s). Digital sections are defined for higher bit rates and guidance on evaluating the performance FO digital sections can be found below.

Note 3 Due to lack of information on the performance of paths operating above 160 Mbit/s, no ESR objectives are recommenced at this time. Nevertheless, ESR processing should be implemented within any error performance measuring devices operating at these rates for maintenance or monitoring purposes. For paths operating at bit rates up to 601 Mbit/s an ESR objective of 0.16 is proposed. This value requires further study.

Table 2 End-to-end error performance objective for a 27 500 km international digital path at or above the primary rate.

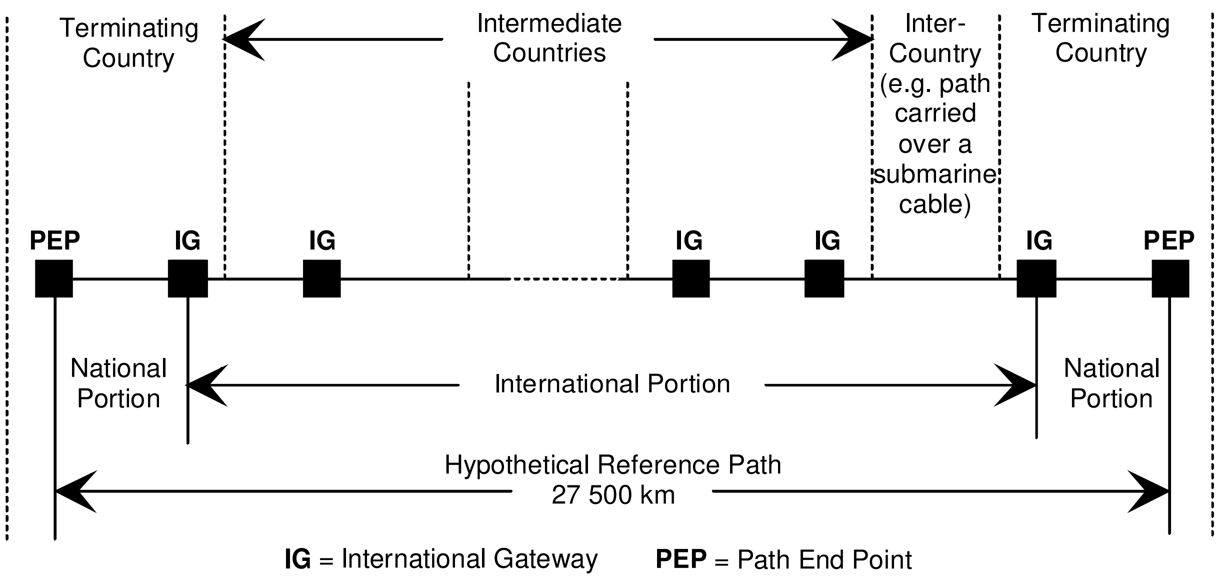


Figure 19 Hypothetical reference path, apportionment methodology G.826

The performance objectives for radio-relay systems as the carrier for the international and national portion are defined in separate ITU-R recommendations.

5.6.1.3.1 International portion using radio-relay systems

The ITU-R Recommendation F.1092-1 [25] defines the "Error performance objectives for constant bit rate digital path at or above the primary rate carried by digital radio-relay systems which may form part of the international portion of a 27 500 km hypothetical reference path". The objectives are based on the overall recommendation given in ITU-T G.826, but adopted to radio-relay systems with reference length of about 1000 km.

Rate (Mbit/s)	***1.5 to 5***	***>5 to 15***	***>15 to 55***	***>55 to 160***	***>160 to 3500***
Errored second ratio	$0.04x(F_L+B_L)$	$0.05x(F_L+B_L)$	$0.075x(F_L+B_L)$	$0.16x(F_L+B_L)$	Under study
Severely errored seconds ratio	$0.002x(F_L+B_L)$				
Background block error ratio	$2x10^{-4}x(F_L+B_L)$ *)	$2x10^{-4}x(F_L+B_L)$			

**) For systems designed prior to 1996: 3x10-4*

distance allocation factor	$F_L = 0.01 \times L / 500$	L(km) ~ 500 km
block allowance factor intermediate countries	$B_L = B_R \times 0.02\ (L / L_{ref})$ $B_L = B_R \times 0.02$	for $L_{min} < L \leq L_{ref}$ for $L > L_{ref}$
block allowance factor terminating countries	$B_L = B_R \times 0.01\ (L / L_{ref}/2)$ $B_L = B_R \times 0.01$	for $L_{min} < L \leq L_{ref}/2$ for $L > L_{ref}/2$
block allowance ratio	$0 < B_R \leq 1$	$B_R = 1$ (under study)
reference length	$L_{ref} = 1000$ km	(provisionally)

Table 3 Error performance objectives for radio-relay systems being part of an international digital path at or above the primary rate.

The performance objective for each direction of a real radio link can be calculated according to ITU-R F.1397 [51]. The value given in the upper part of table 3 should be multiplied by the ratio L_{Link}/L where L_{Link} is the real length of the path ($L_{Link} \geq 50$ km) and L is the system length rounded to the nearest 500 km. As an example, the severely errored seconds objective is 10 SES/month for a 50 km link.

5.6.1.3.2 National portion using radio-relay systems

The ITU-R Recommendation F.1189-1 [26] defines the "Error performance objectives for constant bit rate digital path at or above the primary rate carried by digital radio-relay systems which may form part of the national portion of a 27 500 km hypothetical reference path". The objectives are based on the overall recommendation given in ITU-T G.826, but adopted to radio-relay systems.

Rate (Mbit/s)	*1.5 to 5*	*>5 to 15*	*>15 to 55*	*>55 to 160*	*>160 to 3500*
Errored second ratio	0.04xZ	0.05xZ	0.075xZ	0.16xZ	Under study
Severely errored seconds ratio	0.002xZ				
Background block error ratio	$2\text{x}10^{-4}\text{xZ}$ *)	$2\text{x}10^{-4}\text{xZ}$			$1\text{x}10^{-4}\text{xZ}$

**) For systems designed prior to 1996: 3x10-4*

Long haul section	Z = A	$A = A_1 + (L/500)$	$A_1 = 1 - 2\ \%$
Short haul section	Z = B	fixed block allocation only	B = 7.5 - 8.5 %
Access section	Z = C	fixed block allocation only	C = 7.5 - 8.5 %

$A_1\% + B\% + C\% \leq 17.5\%$ and $15.5\% \leq B\% + C\% \leq 16.5\%$

Table 4 Error performance objectives for radio-relay systems being part of a national digital path at or above the primary rate.

Chapter

6

Antennas

The parabolic antenna is the most commonly used antenna in microwave radio-relay systems. This chapter will introduce the most important antenna parameters from a propagation point of view. A short introduction to passive repeaters is also included at the end of this chapter.

6.1 Antenna parameters

The antenna parameters are very important to the overall system performance. The most important antenna parameters from a propagation point of view are:

- ✧ Gain
- ✧ Side and back lobe levels
- ✧ Beam width
- ✧ Voltage-Standing-Wave-Ratio (VSWR)
- ✧ Discrimination of cross polarization
- ✧ Mechanical stability

6.1.1 Antenna gain

The gain of a parabolic antenna (referred to an isotropic radiator) may be approximated by

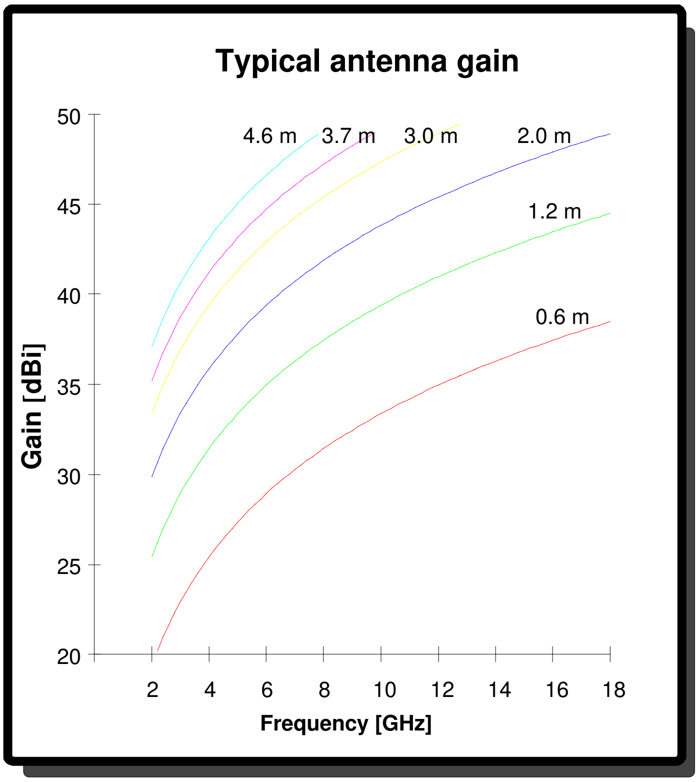
25) $$Gain \approx 10 \log\left(\eta \cdot A \cdot \frac{4\pi}{\lambda^2}\right) \quad [\text{dBi}]$$

where

η = aperture efficiency (typical 0.5 - 0.6)

A = aperture area $\left[\text{m}^2\right]$

λ = wavelength [m]



This formula may be rewritten using the antenna diameter D [m] and the frequency f [GHz] as parameters

(assuming $\eta = 0.55$):

26) $$Gain \approx 17.8 + 20 \log(D \cdot f) \quad [\text{dBi}]$$

The formulas 25) and 26) are only valid in the far field of the antenna. The gain will be less in the near field, and may be obtained from the antenna manufacturer. The cross-over distance between the near and the far-field is approximately:

27) $$d_f \approx \frac{D^2 \cdot f}{0.3} \quad [\text{m}]$$

This gives far-field behaviour at a distance larger than ~180m for a 3m antenna at 6 GHz.

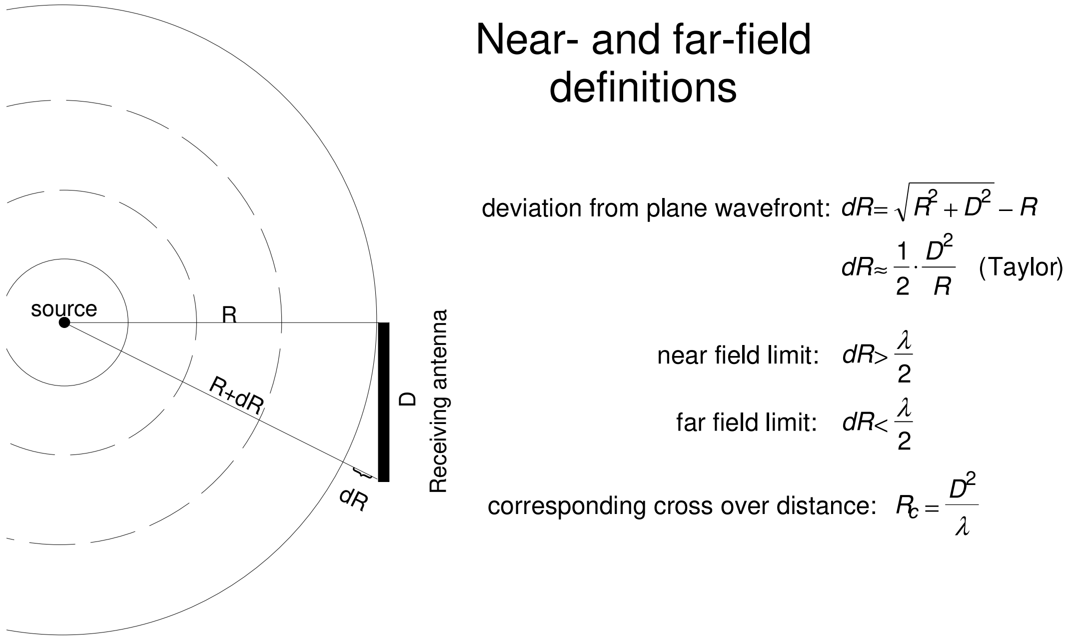


Figure 20 Near- and far-field definitions

6.1.2 VSWR

The voltage-standing-wave-ratio is important to high capacity systems with stringent linearity objectives. To avoid intermodulation interference the VSWR should be minimised for these systems. Standard antennas have a VSWR in the range 1.06 to 1.15 typically. High performance antennas (low VSWR antennas) have a VSWR in the range 1.04 to 1.06 (typically).

6.1.3 Side and backlobe levels

The side and backlobe levels are important parameters in frequency planning and interference calculations. Low side and backlobe levels make a more efficient use of the frequency spectrum possible. The side and backlobe levels are specified (in the far field) in the radiation envelope patterns. The front-to-back ratio gives an indication of the backlobe levels at angles larger than typically 90 degrees. Typically the front-to-back ratio increases with increasing frequency and with increasing antenna diameter.

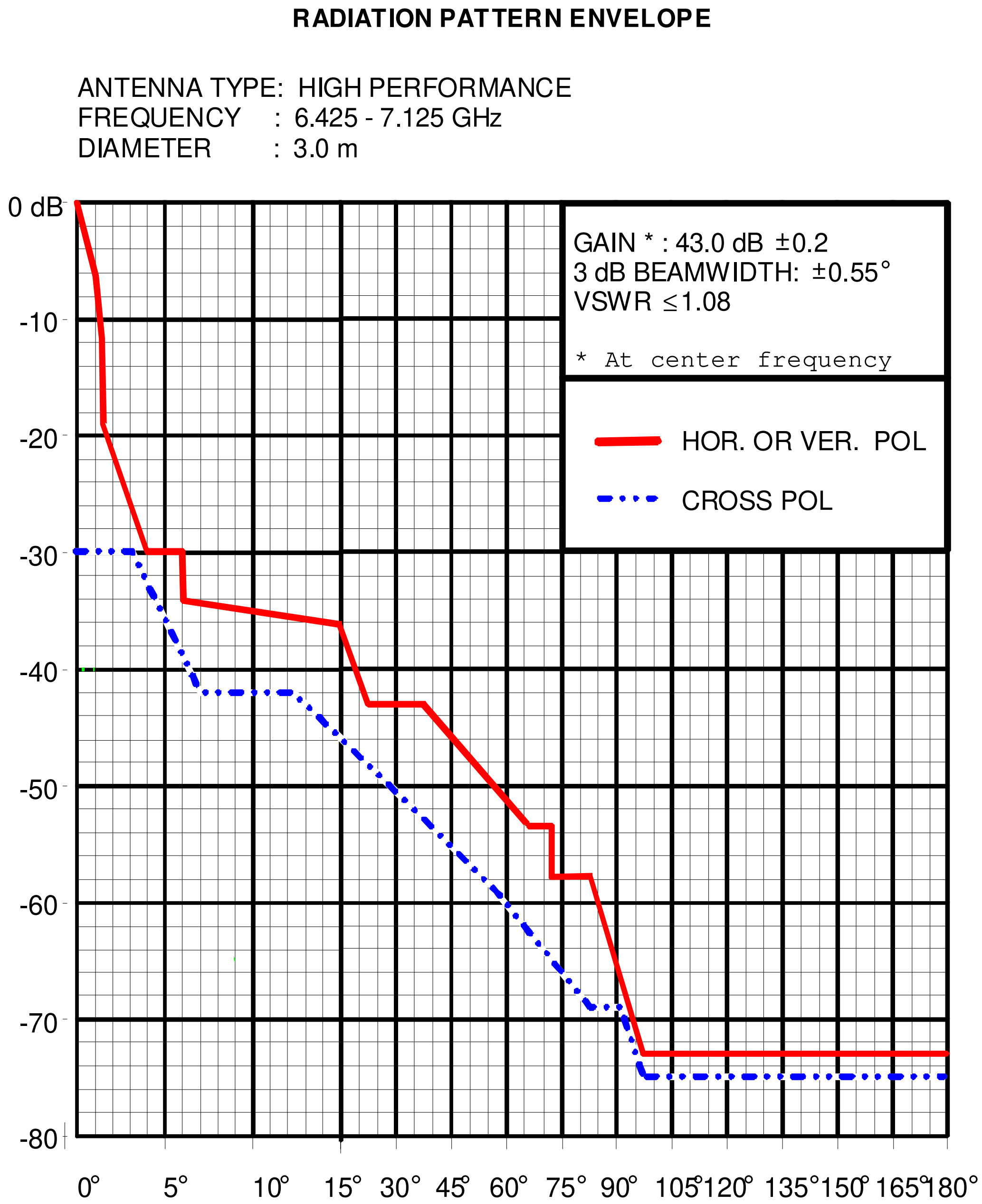


Figure 21 Typical antenna radiation pattern envelope.

6.1.4 Cross-polarization

Another important parameter in frequency planning is the discrimination of cross-polar signals in the antenna. A good cross-polarization enables full utilisation of the frequency band by using both the vertical and the horizontal polarization planes. Typical values are 30 dB for standard antennas and 40 dB for antennas especially designed for cross-polar operation. The discrimination always has the largest value in the main lobe direction.

6.1.5 Beam width

The half power beam width of an antenna is defined as the angular width of the main beam at the -3 dB point as indicated in figure 22. This beam width is approximately found by using [34]

28) $\alpha_{3dB} = \pm 35 \cdot \frac{\lambda}{D}$ degrees

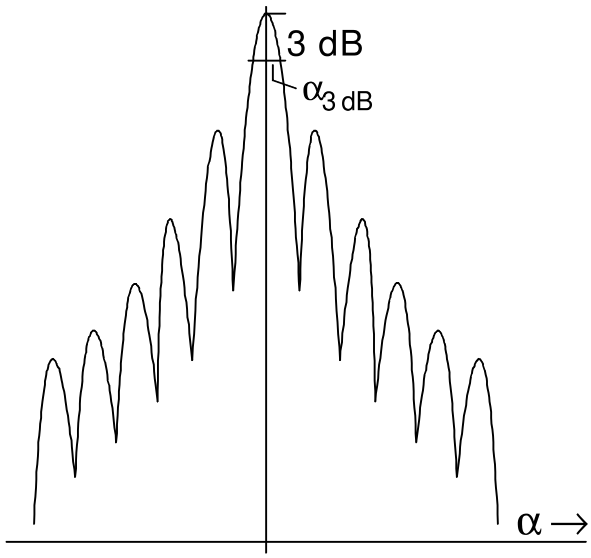


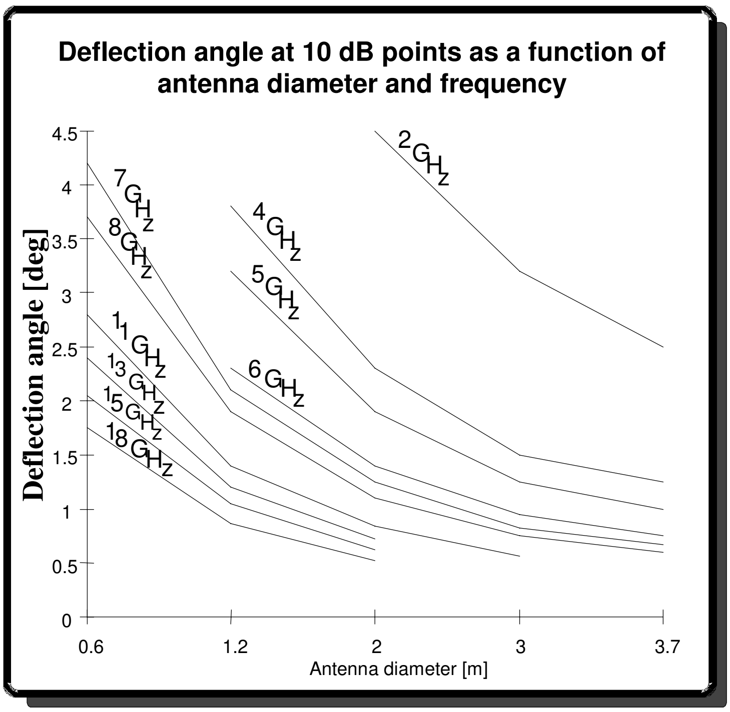
Figure 22 Antenna pattern

The 10 dB deflection angle (single side) may be approximated by

29) $\alpha_{10dB} = 60 \cdot \frac{\lambda}{D}$ degrees

6.1.6 Mechanical stability

Typical limitations in sway/twist for the structure (tower/mast and antenna) correspond to a maximum 10 dB signal attenuation due to antenna misalignment. Using formula 29), the maximum deflection angle may be estimated for a given antenna diameter and frequency.



6.1.7 Effective isotropic radiated power

The effective isotropic radiated power (EIRP) is the actual power radiated by the antenna multiplied by the isotropic power gain of the antenna. Let P_T present the power radiated and G_T the isotropic power gain of the antenna; then

30) $(eirp)_{dBm} = (P_T)_{dBm} + (G_T)_{dBi}$

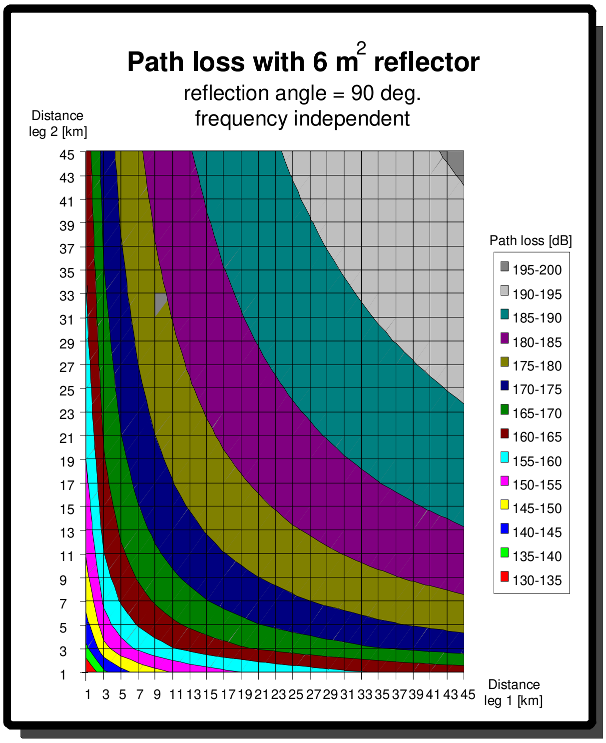
In order to find EIRP in a certain direction the radiation pattern envelope for the given antenna must be used. Commonly the EIRP is given in dBW, and to convert from dBm to dBW 30 must be subtracted from the above formula.

6.2 Passive repeaters

Two types of passive repeaters will be introduced:

- ✧ plane reflectors
- ✧ back-to-back antennas

The plane reflector reflects microwave signals in the same way as a mirror reflects light. The same laws apply. Back-to-back antennas work just like an ordinary repeater station, but without radio frequency transposition or amplification of the signal.



The most used calculation method is to substitute the free space loss in the link budget by

$$A_L = A_{fsA} - G_R + A_{fsB} \quad \text{[dB]} \tag{31)}$$

where

A_{fsA} is the free space loss for the path site A to the passive repeater (figure 23)

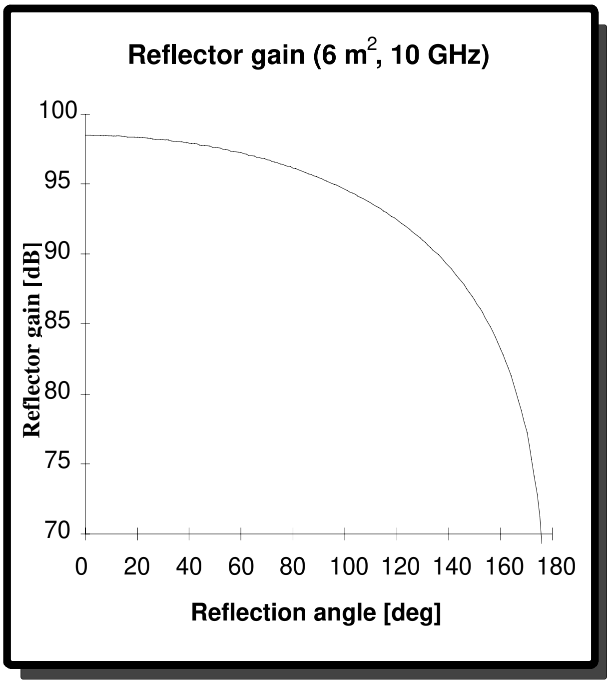
A_{fsB} is the free space loss for the path site B to the passive repeater (figure 23)

G_R is the gain of the passive repeater as given in formula 32) or 35).

The formulas used for calculation of the link budget remain the same with exception of this substitution.

6.2.1 Plane reflectors

Plane reflectors are more popular than back-to-back antennas due to an efficiency close to 100% (50-60% for antennas). Plane reflectors may also be produced with much larger dimensions than parabolic antennas.



6.2.1.1 Gain of plane reflector

The far field gain of a plane reflector is given by:

32) $$G_R = 20\log\left(139.5 \cdot f^2 \cdot A_R \cdot \cos\left(\frac{\psi}{2}\right)\right) \quad \text{[dB]}$$

where

A_R is the physical reflector area in m²

f is the radio frequency in GHz

ψ is the angle in space at the passive repeater in degrees

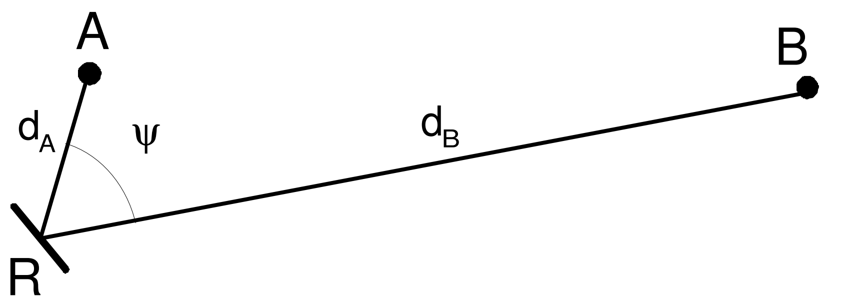


Figure 23 Plane passive reflector geometry.

33) $$\psi = \cos^{-1}\left(\frac{(h_R - h_A)^2 + d_A \cdot d_B \cdot 10^6 \cdot \cos\hat{\psi} - (h_R - h_A)(h_B - h_A)}{\sqrt{\left(d_A{}^2 \cdot 10^6 + (h_R - h_A)^2\right)\left(d_B{}^2 \cdot 10^6 + (h_R - h_B)^2\right)}}\right)$$

where

h_A is the antenna height above sea level at site A in m

h_B is the antenna height above sea level at site B in m

h_R is the height above sea level at the centre of the reflector in m

d_A is the distance from site A to the reflector point in km

d_B is the distance from site B to the reflector point in km

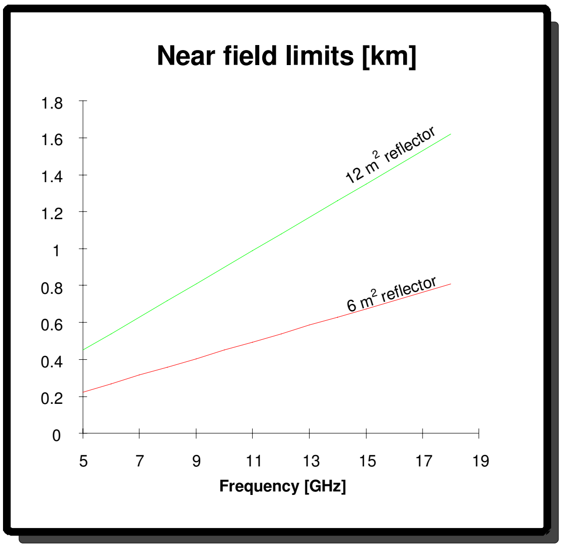
$\hat{\psi}$ is the angle at the reflection point in plane projection in degrees

Unless the legs in figure 23 are extremely steep, $\hat{\psi}$ may be used in place of ψ in equation 32) with good accuracy.

It should be checked whether the passive repeater is in the far-field of the nearest antenna using the formula:

34) $$\delta_s = \frac{75\pi \cdot d_s}{f \cdot A_R \cdot \cos\left(\frac{\psi}{2}\right)}$$

where d_s is the shorter of the two legs $(d_A \text{ and } d_B)$ in figure 23.



If $\delta_s > 2.5$ the passive repeater is in the far-field of the nearest antenna, and formula 32) is valid. [34]

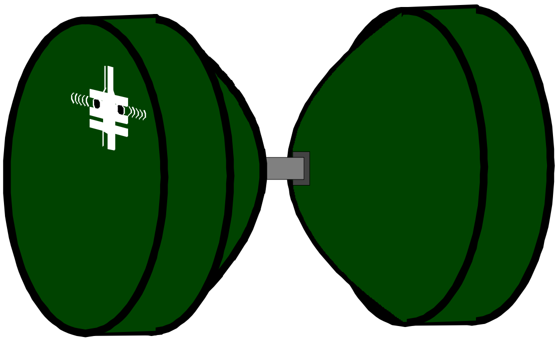
6.2.2 Back-to-back antennas

Use of back-to-back antennas are practical when the reflection angle is large. The gain of a repeater with back-to-back antennas is given by:

35) $$G_R = G_{A1} - A_c + G_{A2} \text{ [dB]}$$

where

G_{A1} is the gain of one of the two antennas at the repeater in dB



G_{A2} is the gain of the other antenna at the repeater in dB

A_c is the coupling loss (waveguide, etc.) between the antennas in dB

Chapter

7

Power budget

In order to estimate the performance of a radio link system, a link power budget has to be prepared. The difference between nominal input level and the radio threshold level, the fading margin, is the main input parameter in the performance prediction model.

7.1 Free space loss

Consider a radiated power P from an isotropic radiator in point A (figure 24). The total radiated power through the sphere is P. By geometry, the power density p in point B is

36) $$p \propto \frac{P}{4\pi d^2}$$

where d is the radius of the sphere (or distance transmitter $\leftrightarrow$ receiver)

Maximum radiated energy from a point source is (Maxwell)

37) $$P \propto \frac{1}{f^2}$$

where f is the radio frequency.

Consequently the receiver power in B is proportional to

38) $$P \propto \frac{1}{f^2 \cdot d^2}$$

This relation gives the free space formula (expressed in dB)

39)
$$L_{fs} = 92.45 + 20\log(d \cdot f)$$

where

d - path length in km

f - frequency in GHz

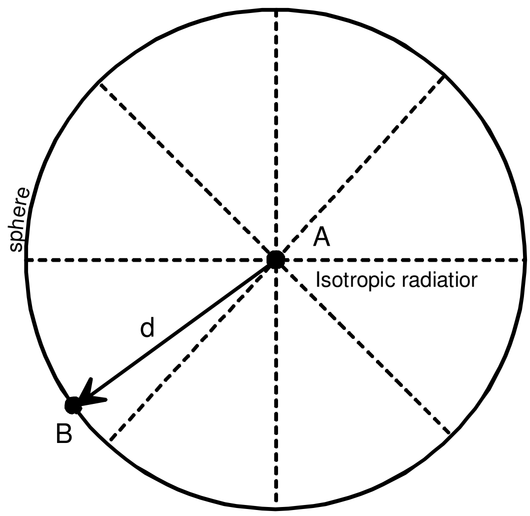


Figure 24 Radiated energy through a sphere

7.2 Atmospheric attenuation

At higher frequencies, above about 15 GHz, the attenuation due to atmospheric gases will add to the total propagation loss of a radio relay path. The attenuation on a path of length d (km) is given by

40) $$A_a = \gamma_a \cdot d \quad \text{dB}$$

where

d - path length in km

γ_a - specific attenuation [dB/km] is given in ITU-R Rec. P.676 [19] which defines the attenuation by atmospheric gases.

The attenuation is due to absorption in uncondensed water vapour and air and the specific attenuation is given by γ_a (dB/km). Both water vapour and air have various absorption lines in the centimetre and millimetre regions. Consequently, there are frequencies where high attenuation occurs and which are separated by frequency bands where the attenuation is substantially lower. The attenuation by air and water vapour is additive and the ITU-R recommendation P.676 appendix 2 formulas for approximate estimation of the specific attenuation $\gamma_a = \gamma_{air} + \gamma_{vapour}$ are valid below 57 GHz.

41) $$\gamma_{air} = \left| \frac{7.27 r_t}{f^2 + 0.351 r_p^2 r_t^2} + \frac{7.5}{(f-57)^2 + 2.44 r_p^2 r_t^5} \right| f^2 r_p^2 r_t^2 \cdot 10^{-3}$$

42)
$$\gamma_{vapour} = \left| \begin{array}{l} 3.27 \cdot 10^{-2} r_t + 1.67 \cdot 10^{-3} \dfrac{\rho r_t^7}{r_p} + 7.7 \cdot 10^{-4} + \dfrac{3.79}{(f-22.235)^2 + 9.81 r_p^2 r_t} \\ + \dfrac{11.73 r_t}{(f-183.31)^2 + 11.85 r_p^2 r_t} + \dfrac{4.01 r_t}{(f-325.153)^2 + 10.44 r_p^2 r_t} \end{array} \right| f^2 \rho r_p r_t \cdot 10^{-4}$$

where f is the frequency in GHz, $r_p = p/1013$, $r_t = 288/(273+t)$, p is pressure in hPa (= mbar), t is temperature in Celsius and ρ is water in (g/m^3). In chapter 2 the calculation of water vapour pressure based on relative humidity in percent H was given. By using the formula

43) $$\rho = \frac{216.7 \cdot e}{T}$$

the water pressure can be converted to (g/m^3). T is the temperature in Kelvin and e is the water vapour pressure in hPa.

Figure 25, presenting the specific attenuation in the 15 to 50 GHz range clearly shows that the attenuation due to water vapour is predominant below 40 GHz. The specific attenuation is most susceptible to changes in ρ. The value ρ=7.5 g/cm^3 used in the figure is the value for the standard atmosphere. Real world values can be found in ITU-R recommendation P836-1 [20].

Near 60 GHz, many oxygen absorption lines merge together, at sea-level pressures, to form a single, broad absorption line. Consequently, only very short path lengths can be realised at frequencies in this range. See ITU-R recommendation P.676 [19] for further details.

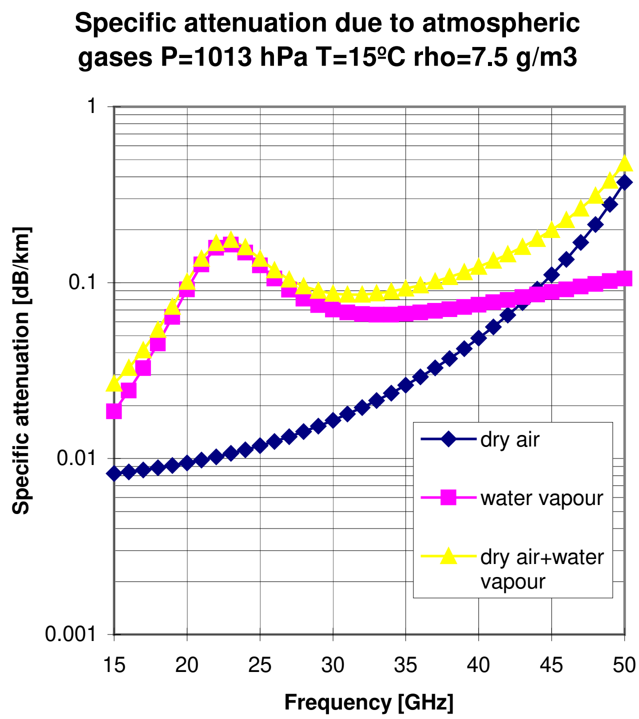


Figure 25 Specific atmospheric attenuation

7.2 Link budget

Figure 26 shows a transmit/receive system that may be used as a simplified model of a radio link system.

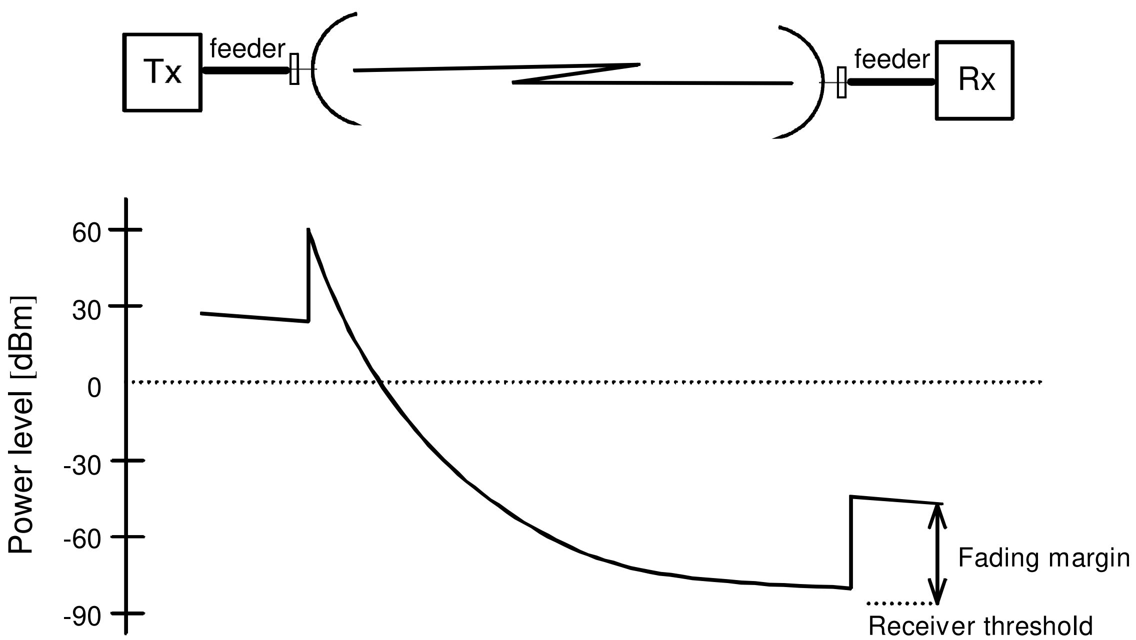


Figure 26 Transmit/receive system

In order to determine the nominal input level and the fading margin for a given path, the set-up shown in "The Bristol channel path" example may be used. If the transmitter output power is defined excluding the channel filter loss, this loss should be subtracted in the calculations. The same applies at the receiver. The branching loss is defined as total branching loss for the hop. The difference between nominal input level and the receiver threshold level is known as the fading margin.

The Bristol channel path (7.5 GHz)

The link budget for the path Ilfracombe - St. Hilary is as follows:

Parameter	*Value*	*Unit*
Transmitter output power	+ 26.0	dBm
Feeder loss transmitter	1.6	dB
Branching loss (Tx/Rx)	1.2	dB
Transmitter antenna gain	42.8	dB
Free space loss	145.5	dB
Receiver antenna gain	42.8	dB
Feeder loss receiver	1.2	dB
Nominal input level	- 37.9	dB
Receiver threshold	- 82.0	dBm
Fading margin	44.1	dB

The atmospheric loss is negligible at 7.5 GHz, but at e.g. 38 GHz this should be taken into consideration as shown below.

AccessLink (5 km path at 38 GHz)

Parameter	*Value*	*Unit*
Transmitter output power	+ 18.0	dBm
Transmitter antenna gain	38.0	dB
Free space loss	138.0	dB
Atmospheric loss	0.5	dB
Receiver antenna gain	38.0	dB
Nominal input level	- 44.5	dB
Receiver threshold	- 80.0	dBm
Fading margin	35.5	dB

Chapter

8

Precipitation

Transmission of microwave signals above ~10 GHz is vulnerable to precipitation. Rain, snow, sleet, ice particles and hail may attenuate and scatter microwave signals and thus result in reduced availability from a system quality point of view. The energy is attenuated due to radiation (scatter) and absorption (heating).

The attenuation due to absorption is larger than attenuation due to scatter for wavelengths that are small compared with the drop size. For wavelengths that are long compared to drop size, the attenuation due to scatter is larger than attenuation due to absorption.

8.1 Characteristics of precipitation

8.1.1 Orographic precipitation

Orographic precipitation is determined by the terrain in the area of interest. Forced uplift of moist air over high ground gives precipitation when the dew point is reached. Figure 27 shows a typical weather condition in western Norway. Moist air from the North Sea approaches the coastline and is forced up by the high mountains close to the shore. The clouds have much smaller water content after passing the mountains and reaching eastern Norway. This is clearly reflected in the regional rainfall statistics of Norway.

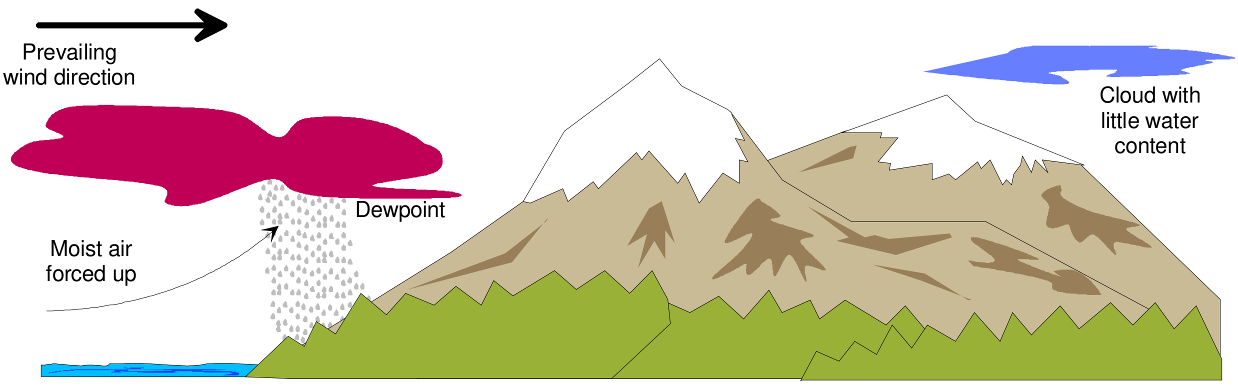


Figure 27 Orographic precipitation

8.1.2 Convectional precipitation

On a hot summer day, heavy clouds may build up in the afternoon due to convection of hot humid air. These clouds may give intense rain (hail) with thunder.

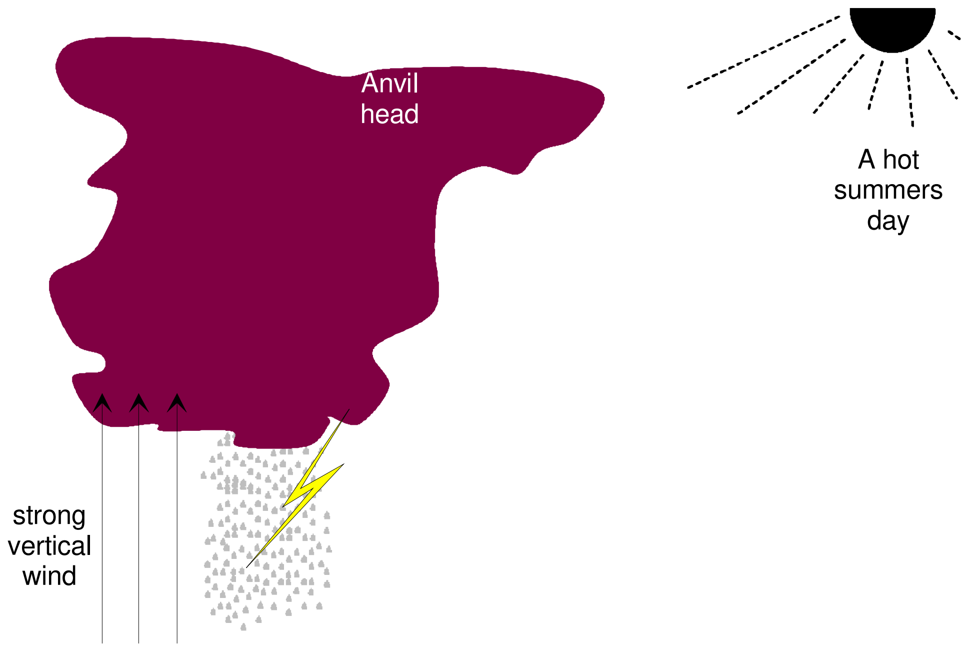


Figure 28 Convectional precipitation

8.1.3 Cyclonic precipitation

Characterised by large scale vertical motions associated with synoptic features such as depressions and fronts.

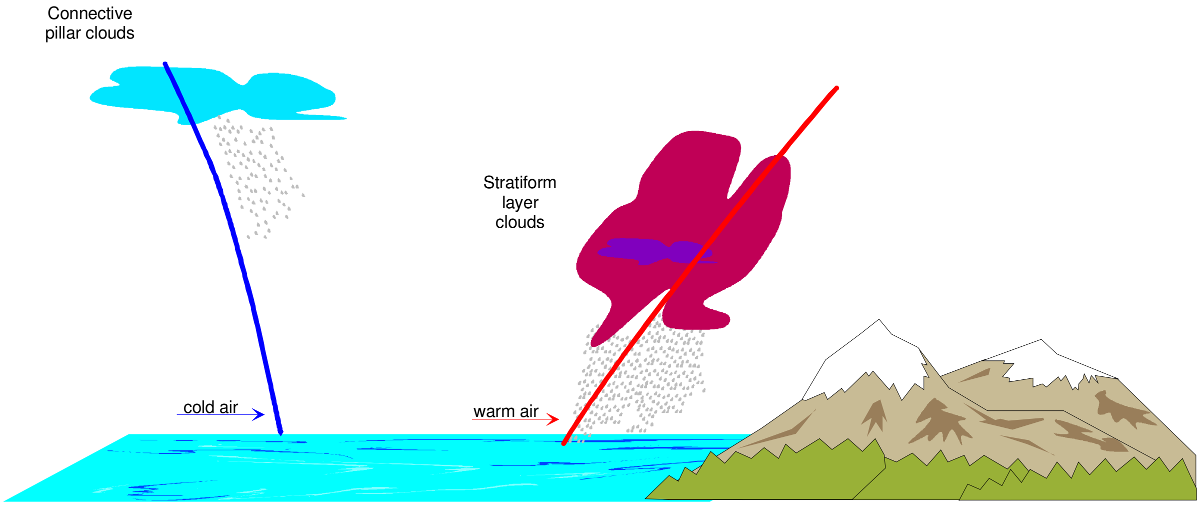


Figure 29 Cyclonic precipitation

8.1.4 Tropical cyclone storms

In tropical areas moving circular storms with intense convective rain may occur with heavy rain 50 - 200 km in diameter. The monsoon rain is a typical example. This is characterised by intense stratiform rainfall for several hours a day and extended over several hundreds of kilometres.

8.2 How precipitation affects radio wave propagation

As mentioned earlier, microwave transmission at 10 GHz or above may be seriously affected by precipitation.

Figure 30 shows a radio relay path where the Fresnel zone is partially filled with rain droplets from a shower. Each particular raindrop will contribute to the attenuation of the wanted signal. The actual amount of fading is dependent on the frequency of the signal and the size of the raindrop.

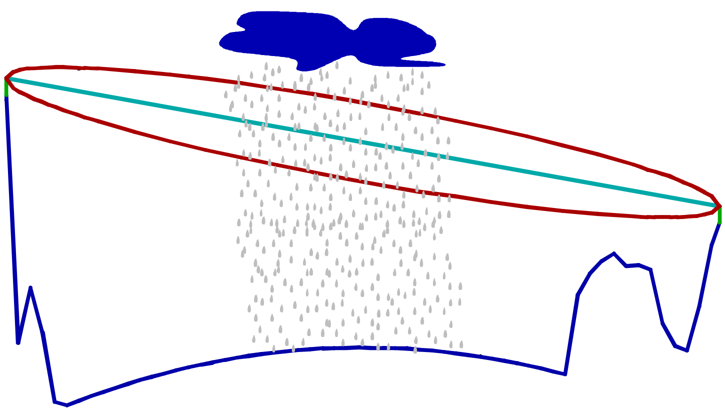


Figure 30 Rain shower

The two main causes to attenuation are scattering and absorption. When the wavelength is fairly large relative to the size of the raindrop, scattering is predominant. Conversely, when the wavelength is small compared to the raindrop size, attenuation due to absorption is dominating.

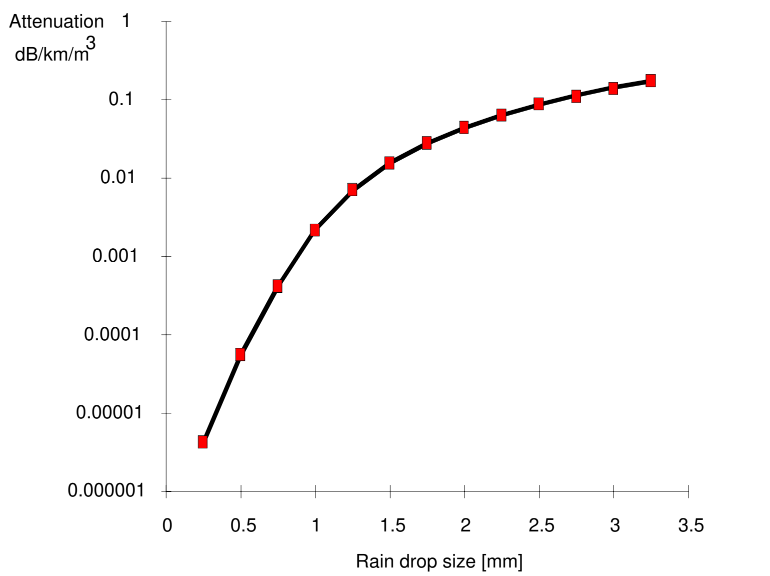
8.2.1 Scattering

Since the radio waves are a time varying electromagnetic field, the incident field will induce a dipole moment in the raindrop. The raindrop dipole will have the same time variation as the radio waves and will therefore act as an antenna and re-radiate the energy. A raindrop is an antenna with low directivity and some energy will be re-radiated in arbitrary directions giving a net loss of energy in the direction towards the receiver.

8.2.2 Absorption

When the wave-length becomes small relative to the raindrop size, more and more energy is absorbed by heating of the raindrop. The radio waves will vary too much in field strength over the raindrop to induce a dipole effect.

Calculated attenuation for one precipitation particle at 10 GHz



for this frequency scattering is predominant

8.2.3 Total rain attenuation for a radio path

In order to calculate the rain induced outage we must know the total amount of raindrops within the Fresnel zone as well as their individual size. The attenuation may be found using

$$A \approx \int_0^{\infty} ND)Q(D,f)\,dD \tag{44}$$

In this formula N is the raindrop size distribution and Q is the attenuation of one particle at a given frequency f. Determining the attenuation using formula 44) is not a very easy task since it is hard to actually count the number of raindrops and measure their individual sizes.

Raindrop size distribution

$N(D) = N_0 \cdot e^{(-aR^b D)}$

$a = 41 \quad b = -0.21$

$N_0 = 0.08$

D = drop diameter [cm]

Higher rain rate;
larger rain drops

An easier method is to measure the amount of rain that hit the ground in some time interval. This is denoted rain rate. The connection between rain rate R and $N(a)$ is given by

$$45) \quad R = 0.6 \cdot 10^{-3} \cdot \pi \int_0^\infty D^3 V(D) N(D) dD$$

where $V(D)$ denote the terminal velocity of the raindrop.

Terminal velocity for rain

$v = a \cdot D^b$ [cm/s]

$a = 1690 \quad b = 0.6$

D = drop diameter [cm]

v = 6.4 m/s
for D = 0.2 cm

Both the terminal velocity and typical rain drop distributions have been studied thoroughly and are well known. So it is possible to estimate the attenuation by considering the rain rate only.

8.2.4 Rain measurements

Rainfall is measured in millimetres [mm], and rain intensity in millimetres pr. hour [mm/h]. Different measurement principles are shown in figure 31.

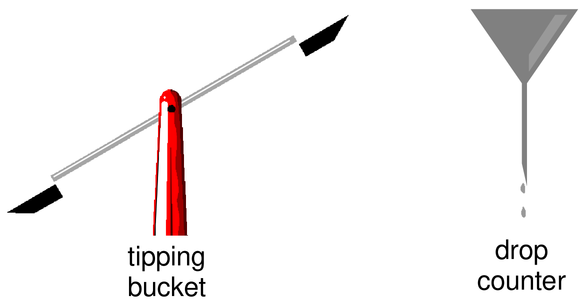
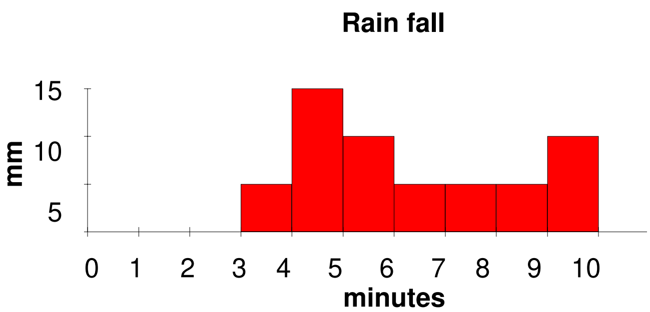


Figure 31 Typical rain gauges

An important parameter is the integration time, e.g. the time between readings of the rainfall. Typical values for the integration time are 1 min, 5 min, 10 min, 1 hour, 1 day. An integration time of 1 minute should be used for rain intensity in link calculations. To illustrate the importance of the integration time, let us look at the example shown in figure 32.



1 min. integration time:
30, 90, 60, 30, 30, 30, 60 mm/h

5 min. integration time:
48, 18 mm/h

10 min. integration time:
33 mm/h

1 hour integration time:
5.5 mm/h

Figure 32 Rain rate and integration time

8.2.5 Raindrop shape

As the raindrops increase in size, they depart from the spherical shape (see figure 33). This deviation from the spherical shape results that the raindrops are more extended in the horizontal direction and consequently will attenuate horizontal polarized waves more than the vertical polarized. This means that vertical polarization is favourable at high frequencies where outage due to rain is dominant.

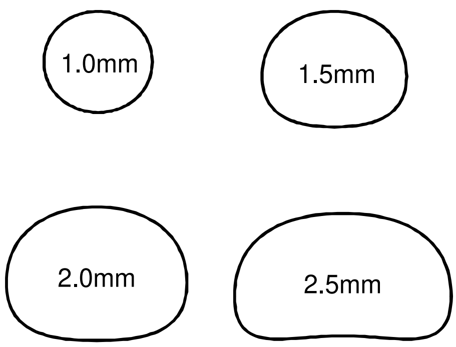


Figure 33 Raindrop shape with varying size of the equivalent sphere.

8.3 Unavailability due to rain

8.3.1 Effective path length

Since rain has a tendency to cluster (especially at high rain rates), only parts of a typical radio link path will be affected by rain. The effective path length containing rain cells is given by

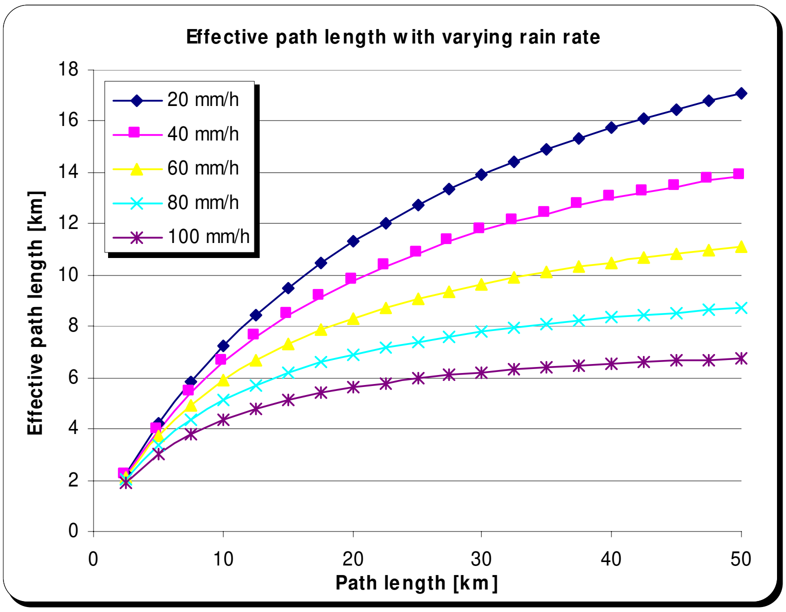
46) $$\psi = \frac{d}{1 + \left| \dfrac{d}{35 \cdot e^{-0.015 \cdot R}} \right|}$$

for R > 100 mm/h: R = 100 mm/h

d is the path length in km

R is the rain intensity in mm/h for 0.01% of the time.

If you do not have local information on the rain intensity, this may be found using in table 5 and the rain zone contour maps in figures B1 through B3 in appendix B [32]. Alternatively the rainfall contour maps in figures C1 through C3 in appendix C [28] may be used.



Percentage of time (%)	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q
1.0	<0.1	0.5	0.7	21	0.6	1.7	3	2	8	1.5	2	4	5	12	24
0.3	0.8	2	2.8	4.5	2.4	4.5	7	4	13	4.2	7	11	15	34	49
0.1	2	3	5	8	6	8	12	10	20	12	15	22	35	65	72
0.03	5	6	9	13	12	15	20	18	28	23	33	40	65	105	96
0.01	8	12	15	19	22	28	30	32	35	42	60	63	95	145	115
0.003	14	21	26	29	41	54	45	55	45	70	105	95	140	200	142
0.001	22	32	42	42	70	78	65	83	55	100	150	120	180	250	170

Table 5 Rainfall intensity exceeded [mm/h] [32].
(Reference to figures B1 through B3 in appendix B.)

8.3.2 Fade depth due to rain

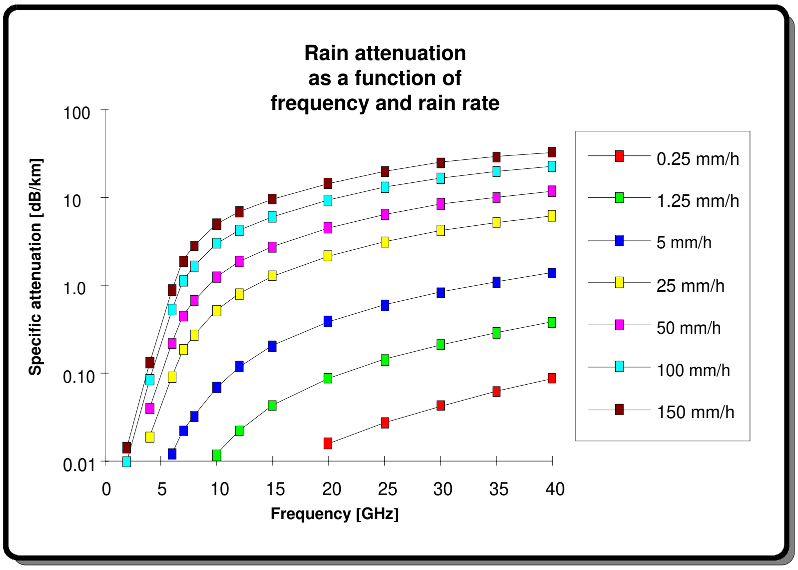
As seen earlier, the rain rate R was connected to the drop size distribution and the terminal velocity of the rain drops. Knowing R, it is possible to calculate the amount of raindrops and their size within the Fresnel zone. The specific attenuation (dB/km) is given by:

47) $\gamma_r = k \cdot R^{\alpha}$

where

k and α are given in table 6 and vary with radio frequency and polarization.

The attenuation due to rain in 0.01% of the time for a given path may be found by



48) $A_{0.01} = \psi \cdot k \cdot R^{\alpha}$ [dB]

Frequency [GHz]	k_h	k_v	α_h	α_v
1	0.0000387	0.0000352	0.912	0.880
2	0.0001540	0.0001380	0.963	0.923
4	0.0006500	0.0005910	1.121	1.075
6	0.0017500	0.0015500	1.308	1.265
7	0.0030100	0.0026500	1.332	1.312
8	0.0045400	0.0039500	1.327	1.310
10	0.0101000	0.0088700	1.276	1.264
12	0.0188000	0.0168000	1.217	1.200
15	0.0367000	0.0335000	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929

Table 6 Regression coefficients for estimating specific attenuation in equation 47). [30]

The relation between fading margin and unavailability for the path is given by

49) $F = 0.12 \cdot A_{0.01} \cdot P^{-(0.546+0.043 \cdot \log P)}$ [dB]

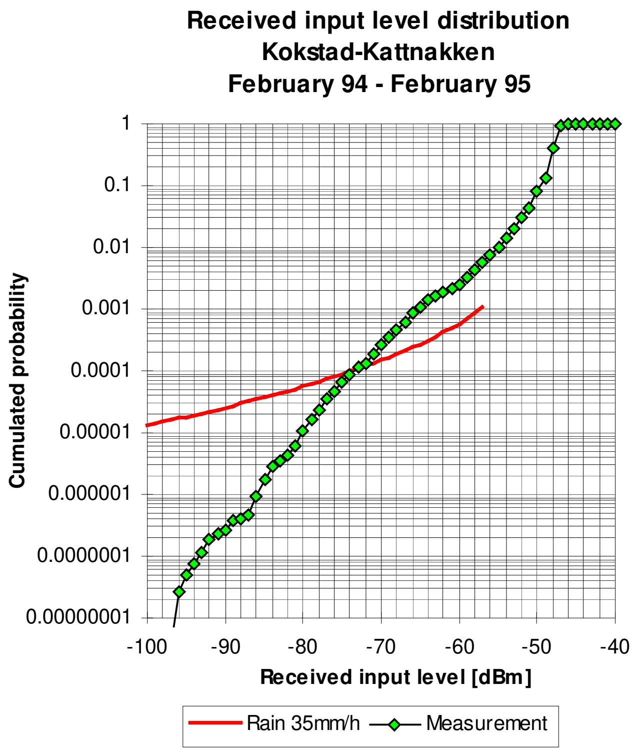
where P is the unavailability in percent

Formula 49) is used to scale to other percentages of time than 0.01%. [31]

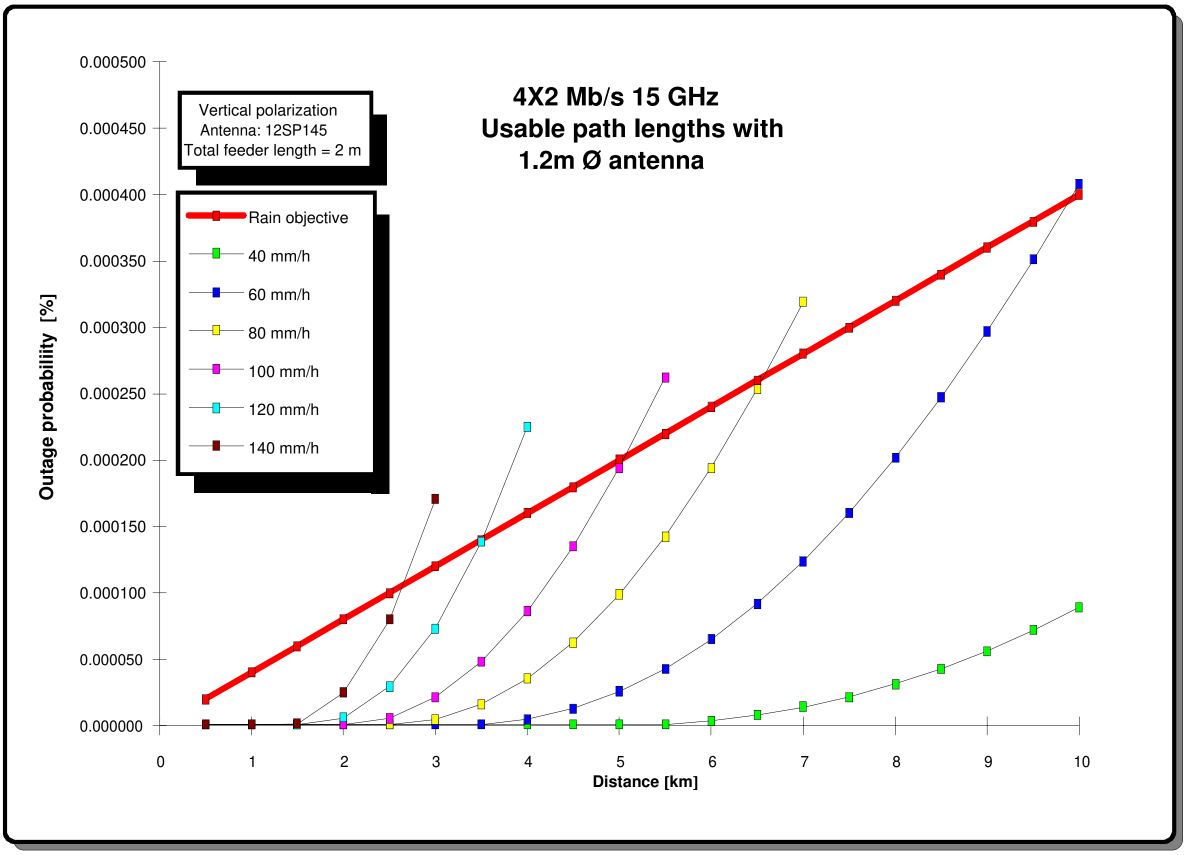
The unavailability may be found solving equation 49) with respect to *P*.

50) $$P = 10^{11.628\left(-0.546+\sqrt{0.29812+0.172\log\left(0.12\cdot A_{0.01}/F\right)}\right)} \quad [\%]$$

To avoid imaginary values, use $A_{0.01}/F = 0.155$ in cases where $A_{0.01}/F < 0.154023$.



The figure shows the received input level, vertically polarized, on a 48 kilometre 15 GHz test path in western Norway where the rainrate is approximately 35 mm/h. The purpose of this one year test was to check the validity of the unavailability due to rain prediction models given by the ITU-R and investigate the amount of outage due to snow and sleet. A clear discrepancy between the measured results and ITU-R prediction models was observed, and it seems to be possible to allow longer 15 GHz paths than the prediction indicates. The outage on the path was caused by late summer rain showers. Fades due to sleet and snow were negligible when compared to fades due to rain.


4X2 Mb/s 15 GHz
Usable path lengths with
1.2m Ø antenna
Vertical polarization
Antenna: 12SP145
Total feeder length = 2 m
Rain objective
40 mm/h
60 mm/h
80 mm/h
100 mm/h
120 mm/h
140 mm/h
Outage probability [%]
0.000500
0.000450
0.000400
0.000350
0.000300
0.000250
0.000200
0.000150
0.000100
0.000050
0.000000
0
1
2
3
4
5
6
7
8
9
10
Distance [km]

Chapter

9

Performance predictions

Atmospherical disturbances affect the transmission conditions for L.O.S. radio links. The received signal will vary with time, and the system performance is determined by the probability for the signal level to drop below the radio threshold level or the received spectrum to be severely distorted. Different calculation models will be discussed in this chapter.

9.1 Why fading margin?

Figure 34 shows the input level as a function of time during a fading event. The input level is found to be below the radio threshold level for relatively short periods of time. This time gives system performance degradation and possibly outage. Fading events are mainly caused by multipath fading and fading due to precipitation. As figure 34 shows, the larger fading margin, the smaller probability for the signal to drop below the receiver threshold level. Consequently, the system performance is improved by increased fading margin. This may be achieved by higher output level, larger antennas, lower threshold level, reduced path length, etc.

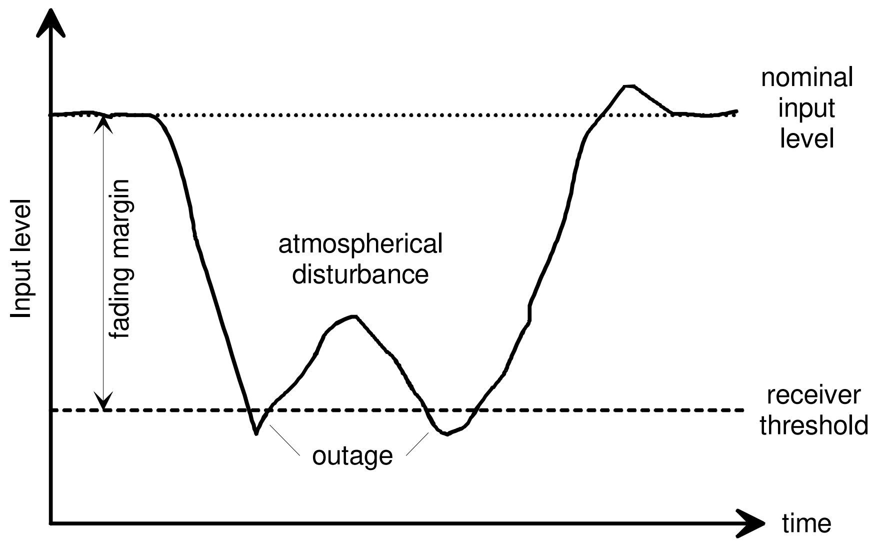


Figure 34 Fading event

9.2 Multipath fading

Fading due to layering of the atmosphere is the dominating factor of degradation of radio-relays.

Meteorological conditions in the space separating the transmitter and the receiver may sometimes cause detrimental effects to the received signal. Rays that normally would have been lost in the troposphere may be refracted into the receiving antenna where they are added to the wanted signal. The phase- and amplitude relationship between signals determines the resulting input signal at the receiver.

This affects the transmission of digital signals in two ways. In some occasions, all components of the useful signal spectrum will be equally reduced. This is called non-selective or "flat" fading.

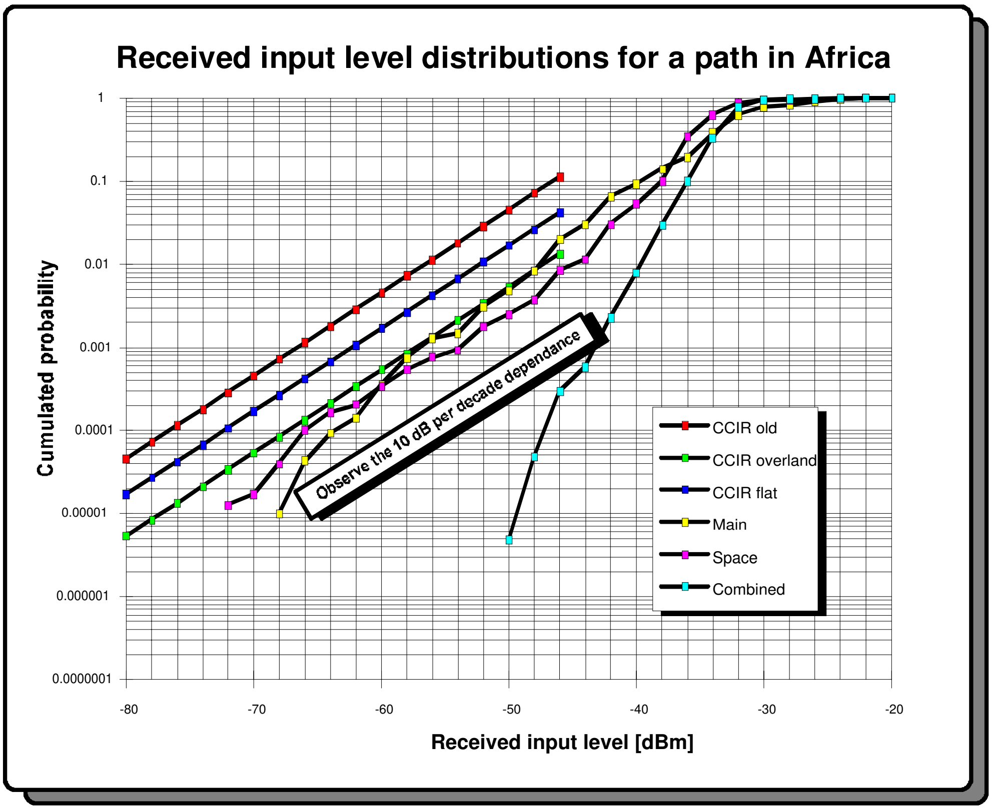
Other times only some of the spectral components will be reduced, causing the spectrum to be distorted. This is called frequency selective fading. These two effects will be treated separately.

The total outage due to multipath fading is the sum of the flat outage and the selective outage.

51) $$P_{tot} = P_{flat} + P_{sel}$$

9.2.1 Flat fading

Measurements in different parts of the world, ITU-R report 338-6 [18] and recommendation P.530 [31], indicate that the probability that the received level will fade F dB below free-space level is:



52) $$P_{flat} = P_0 \cdot 10^{-F/10}$$

where F equals the fading margin

The parameter P_o, the fading occurrence factor, is related to well-defined path parameters.

9.2.1.1 Old prediction method

The fading occurrence factor in 52) is a function of the path location, the terrain and the radio frequency used (Barnett and Vigants [18]):

53) $$P_0 = 0.3 \cdot a \cdot b \cdot \frac{f}{4} \cdot \left(\frac{d}{50}\right)^3$$

where a is a climatic factor given in table 7.

f is the radio frequency in GHz

d is the path length in km

54) $$b = \left(\frac{15}{S}\right)^{1.3}$$ please note: $6 \text{ m} < S < 42 \text{ m}$

where

S is the standard deviation (RMS) of the terrain elevations, measured in 1 km intervals along the path, excluding the radio sites.

a	climatic region
4.00	Equatorial, high humidity and temperature regions, annual mean value of N is about 360 N-units.
3.00	Deserts, strong thermal variations from day to night time, the value of N is about 280 N-units, but this varies strongly. Also coastal regions with fairly flat terrain in more temperate climates.
2.00	Maritime temperate overland, radio ducts quite common for small percentages of the time, fairly dry climate.
1.50	Continental subtropical, dry winter and rainy summer, often radio ducts over dry land, mean value of N is about 320 N-units, but the variation is almost 100 N-units during a year.
1.00	Continental temperate, midlatitude, average rolling terrain, strong diurnal temperature variation, propagation conditions most favourably in the summer, mean value of N is 320 N-units, and the variation is about 20 to 40 N-units throughout the year.
0.50	High, fairly dry regions, inland region, average terrain.
0.25	Mountains, strongly rolling terrain, fairly dry.
0.05	Polar, relatively low temperatures and little precipitation.

Table 7 Climatic regions.

9.2.1.2 New prediction method

ITU-R recommendation P.530 [31] gives a new method for calculating the fading occurrence factor for the worst month. No path profile is required for this method, but a general classification of the path type gives a more accurate prediction.

The methods are derived from fading data on paths with lengths in the range 7-95 km, frequencies in the range 2-37 GHz, path inclinations for the range 0-24 mrad, and grazing angles in the range 1-12 mrad. Checks using several other sets of data for paths up to 237 km in length and frequencies as low as 500 MHz, suggest however, that it is valid for larger ranges of path length and frequency. The results of a semi-empirical analysis indicate that the lower frequency limit of validity is inversely proportional to path length. A rough estimate of this lower frequency limit, f_{min}, can be obtained from:

55) $$f_{min} = 15 / d \qquad \text{GHz}$$

The outage probability (in percent) for the worst month is given by

56) $$P_{flat} = P_0 \cdot 10^{-F/10}$$

and the fading occurrence factor is

57) $$P_0 = K \cdot d^{3.6} \cdot f^{0.89} \cdot (1 + |E_p|)^{-1.4}$$

where K - geoclimatic factor

d - path length [km]

f - frequency [GHz]

$E_p = \dfrac{|h_1 - h_2|}{d}$ - Path inclination [millirad]

h_1, h_2 - antenna heights above mean sea level [m]

The geoclimatic factor may be estimated for the average worst month from fading data. In absence of such data empirical relations must be used based on the type of path.

9.2.1.2.1 Inland links

Inland links are those in which either the entire path profile is above 100 m altitude (with respect to mean sea level) or beyond 50 km from the nearest coastline, or in which part or all of the path profile is below 100 m altitude for a link entirely within 50 km of the coastline, but there is an intervening height of land higher than 100 m between this part of the link and the coastline. Links passing over a river or a small lake should normally be classed as passing over land. The geoclimatic factor K is then given by

58) $$K = 5 \cdot 10^{-7} \cdot 10^{-0.1\left(C_0 - C_{Lat} - C_{Lon}\right)} P_L^{\,1.5}$$

P_L is the percentage of time that the average refractivity gradient in the lowest 100 metre of the atmosphere is less than -100 N-units/km.

The figures 8 through 11 of ITU-R report 563 [28] give P_L for four different months. The month that has the highest value should be chosen. These figures are given in Appendix A.

The value of the coefficient C_0 in equation 58) is given in Table 8 for three ranges of altitude of the lower of the transmitting and receiving antennas and three types of terrain (plains, hills, or mountains). In cases of uncertainty as to whether a link should be classified as being in a plain or hilly area, the mean value of the coefficients C_0 for these two types of area should be employed. Similarly, in cases of uncertainty as to whether a link should be classified as being in a hilly or mountainous area, the mean value of the coefficients C_0 for these two types of area should be employed. Links traversing plains at one end and mountains at the other should be classified as being in hilly areas. For the purposes of deciding whether a partially overwater path is in a largely plains, hilly, or mountainous area, the water surface should be considered as a plain.

For planning purposes where the type of terrain is not known, the following values of the coefficient C_0 in equation 58) should be employed:

$C_0 = 1.7$	for lower-altitude antenna in the range 0-400 m above mean sea level
$C_0 = 4.2$	for lower-altitude antenna in the range 400-700 m above mean sea level
$C_0 = 8$	for lower-altitude antenna more than 700 m above mean sea level

The coefficient C_{Lat} in equation 58) of latitude ξ is given by:

$C_{Lat} = 0$	(dB)	for $\xi \leq 53°$ N or °S
$C_{Lat} = -53 + \xi$	(dB)	for $53°$ N or °S $< \xi < 60°$ N or °S
$C_{Lat} = 7$	(dB)	for $\xi \geq 60°$ N or °S

and the longitude coefficient C_{Lon}, by:

$C_{Lon} = 3$	(dB)	for longitudes of Europe and Africa
$C_{Lon} = -3$	(dB)	for longitudes of North and South America
$C_{Lon} = 0$	(dB)	for all other longitudes

Altitude of lower antenna and type of link terrain	C_0 (dB)
Low altitude antenna (0-400 m) – Plains: Overland or partially overland links, with lower-antenna altitude less than 400 m above mean sea level, located in largely plains areas	0
Low altitude antenna (0-400 m) – Hills: Overland or partially overland links, with lower-antenna altitude less than 400 m above mean sea level, located in largely hilly areas	3.5
Medium altitude antenna (400-700 m) – Plains: Overland or partially overland links, with lower-antenna altitude in the range 400-700 m above mean sea level, located in largely plains areas	2.5
Medium altitude antenna (400-700 m) – Hills: Overland or partially overland links, with lower-antenna altitude in the range 400-700 m above mean sea level, located in largely hilly areas	6
High altitude antenna (>700 m) – Plains: Overland or partially overland links, with lower-antenna altitude more than 700 m above mean sea level, located in largely plains areas	5.5
High altitude antenna (>700 m) – Hills: Overland or partially overland links, with lower-antenna altitude more than 700 m above mean sea level, located in largely hilly areas	8
High altitude antenna (>700 m) – Mountains: Overland or partially overland links, with lower-antenna altitude more than 700 m above mean sea level, located in largely mountainous areas	10.5

Table 8 Values of coefficient C_0 in equations 58) and 60) for three ranges of lower antenna altitude and three types of terrain

The value of the climatic variable P_L in equation 58) is estimated by taking the highest value of the –100 N units/km gradient exceedance from the maps for the four seasonally representative months of February, May, August and November given in Figs. 7-10 of Recommendation ITU-R P.453. An exception to this is that only the maps for May and August should be used for latitudes greater than 60° N or 60° S.

9.2.1.2.2 Coastal links over/near large bodies of water

The link may be considered to be crossing a coastal area if a fraction r_c of the path profile is less than 100 m above the mean level of a medium-sized or large body of water and within 50 km of its coastline, and if there is no height of land above the 100 m altitude (relative to the mean altitude of the body of water in question) between this fraction of the path profile and the coastline.

If measured data for K are not available for coastal links over/near large bodies of water, K can be estimated from:

59) $$K = \begin{cases} K_l\ (r_c) = 10^{(1 - r_c) \log K_i + r_c \log K_{cl}} & \text{for } K_{cl} \geq K_i \\ K_i & \text{for } K_{cl} < K_i \end{cases}$$

where r_c is the fraction of the path profile below 100 m altitude above the mean level of the body of water in question and within 50 km of the coastline, but without an intervening height of land above 100 m altitude, K_i is given by the expression for K in equation 58), and:

60) $$K_{cl} = 2.3 \times 10^{-4} \times 10^{-0.1C_0 - 0.011\,|\xi|}$$

with C_0 given in Table 8. Note that the condition $K_{cl} < K_i$ in equation 59) occurs in a few regions at low and mid latitudes.

9.2.1.2.3 Coastal links over/near medium-sized bodies of water

If measured data for K are not available for coastal links over/near medium-sized bodies of water, K can be estimated from:

61) $$K = \begin{cases} K_m\ (r_c) = 10^{(1 - r_c) \log K_i + r_c \log K_{cm}} & \text{for } K_{cm} \geq K_i \\ K_i & \text{for } K_{cm} < K_i \end{cases}$$

and:

62) $$K_{cm} = 10^{0.5\,(\log K_i + \log K_{cl})}$$

with K_{cl} given by equation 60). Note that the condition $K_{cm} < K_i$ in equation 61) occurs in a few regions at low and mid latitudes.

The size of a body of water can be chosen on the basis of several known examples: Medium-sized bodies of water include the Bay of Fundy (east coast of Canada) and the Strait of Georgia (west coast of Canada), the Gulf of Finland, and other bodies of water of similar size. Large bodies of water include the English Channel, the North Sea, the larger reaches of the Baltic and Mediterranean Seas, Hudson Strait, and other bodies of water of similar size or larger.

9.2.1.2.4 Indistinct path definition

There might be cases where a distinct path definition is difficult, or detailed information about the individual paths is missing. In this case the following guidelines may be used.

In cases of uncertainty as to whether the size of body of water in question should be classed as medium or large, K should be calculated from:

63) $$K = 10^{(1 - r_c)\log K_i + 0.5 r_c (\log K_{cm} + \log K_{cl})}$$

Regions (not otherwise in coastal areas) in which there are many lakes over a fairly large area are believed to behave somewhat like coastal areas. The region of lakes in southern Finland provides the best known example. Until such regions can be better defined, K should be calculated from:

64) $$K = 10^{0.5[(2 - r_c)\log K_i + r_c \log K_{cm}]}$$

9.2.2 Frequency selective fading

The performance of line-of-sight (LOS) digital radio links can be seriously impaired by frequency selective fading, due to in-band amplitude and phase distortions. This multipath (or selective) fading can be a result of surface reflections, or induced by atmospheric anomalies such as strong ducting gradients.

During some stagnant, horizontally layered atmospheric conditions, the vertical gradient in atmospheric index of refraction produces multiple propagation paths between the transmitter and the receiver of a LOS microwave radio link as shown in figure 35. Figure 36 shows the resulting time domain impulse response of the multipath radio link in figure 35. This impulse response during multipath propagation condition indicates that the radio will receive multiple pulses for each digital pulse sent from the transmitter. These figures illustrate only the simplified case of two rays. However, a more complicated three-ray model is used in analyses and will be described later.

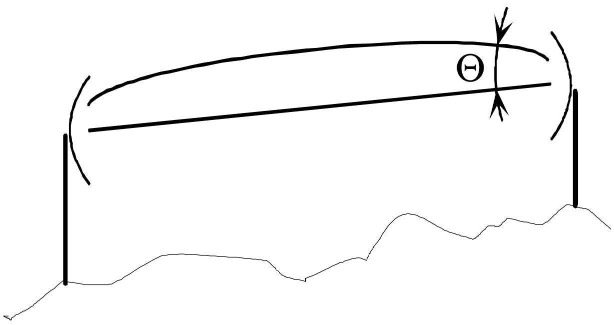


Figure 35 Simplified two-ray model.

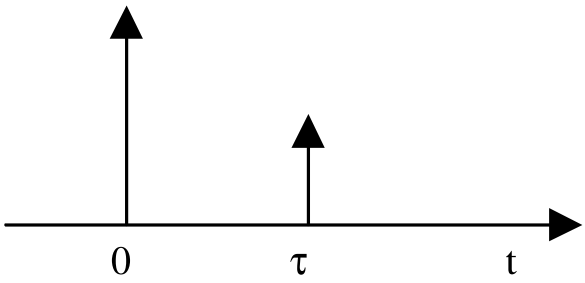


Figure 36 Time domain response for two-ray model

If τ is the relative time delay between the two propagation paths shown in figure 35, the relative phase between the two paths is $2\pi f \cdot \tau$ and thus a function of the frequency, f. The amplitude and the phase of the received signal vary with frequency as indicated by the transfer function of the radio link in figure 37. Such frequency variation in the transfer function of the radio link is known as *frequency selective fading*.

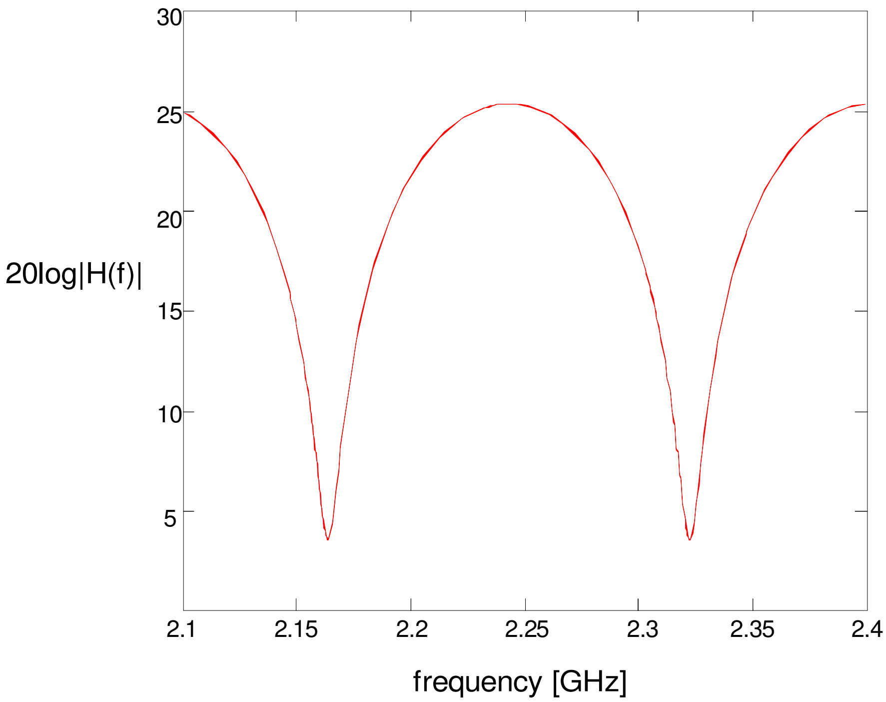


Figure 37 The transfer function of the transmission path.

The impacts of multipath fading on digital radio can be briefly summarised as follows:

- It reduces the signal-to-noise ratio and consequently increases the bit-error-rate (BER).
- It reduces the carrier-to-interference ratio (CIR) and consequently increases the BER.
- It distorts the digital pulse waveform resulting in increased intersymbol interference and BER.
- It introduces crosstalk between the two orthogonal carriers, the I-rail and the Q-rail, and consequently increases the BER.

Clearly the multipath dispersive fading can seriously degrade the performance and cause outages and disruptions of a digital radio system through several mechanisms.

There are a number of different methods for predicting outages due to frequency selective fading. Nera has chosen to use a signature curve method described in ITU-R. report 784-3 [29]. This method agrees reasonably well with measured results and clearly shows the radio's ability to withstand the selective fading.

65) $$P_{sel} = 4.3 \cdot 10^{-1} \cdot \eta \cdot sf \cdot \frac{\tau_m{}^2}{\tau_0}$$ (in percent)

where η is related to the fading occurrence factor P_o (given in formula 57). η is often called the fading activity factor:

66) $$\eta = 1 - \exp\left(-0.2 \cdot \left(\frac{P_0}{100}\right)^{3/4}\right)$$

τ_m is the typical path echo delay given by :

67) $$\tau_m = 0.7 \cdot \left(\frac{d}{50}\right)^{1.5}$$

d is the path length in km and *sf* is called the equipment signature factor.

τ_0 is the echo delay time used during measurement of the signature curves. A much used value (also used by Nera) is:

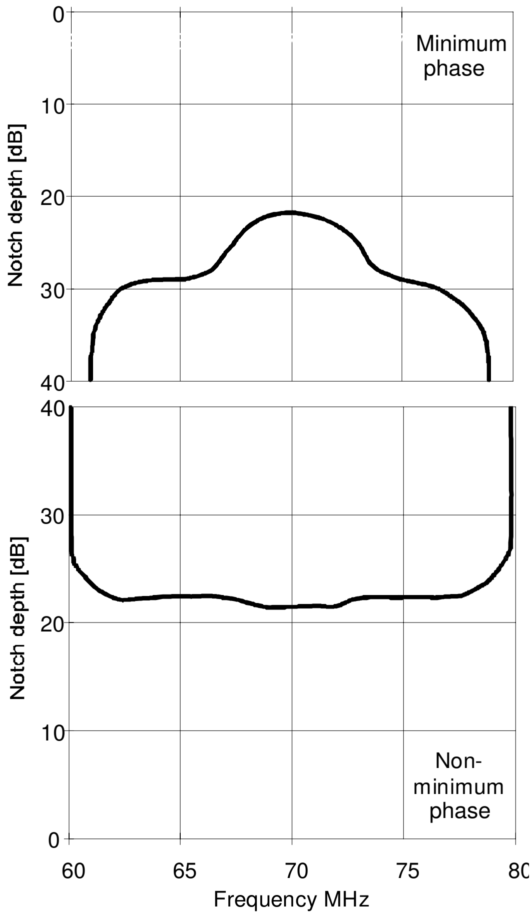
$$\tau_0 = 6.3 \text{ ns}$$

The signature factor *sf* is derived from the signature curve of the equipment, using the formula :

$$sf = \int_{-W/2}^{W/2} 10^{\frac{-B_c}{20}} \, dW \tag{68}$$

W - signature bandwidth

B_c - critical value of the notch depth to produce the Bit Error Rate (BER) of 10^{-3} or 10^{-6} on the signature curve



Typical signature curve
NL290 155 Mb/s SDH
BER: 1E-3, delay: 6.3 ns

The signature factor *sf* represents the area described by the signature curve of the radio. *sf* is calculated for both minimum phase and non-minimum phase fade, and the arithmetic mean is used.

It should be noted that the signature factor *sf* is strongly dependent on the method of modulation.

If the signature factor is not known, the selective fading occurrence may be calculated using the signature envelope defined by the signature depth and width. The prediction will be more conservative as using this envelope results in a larger value of the signature area compared to the actual curve.

69) $$P_s = 2.15\eta \left| W_M \times 10^{-B_M/20} \frac{\tau_m^2}{|\tau_0|} + W_{NM} \times 10^{-B_{NM}/20} \frac{\tau_m^2}{|\tau_0|} \right|$$

where

W_x: signature width (GHz)
B_x: signature depth (dB)

The Bristol channel path

ST. HILARY:		ILFRACOMBE:	
Ant. height:	136.0m / 143.5m (a.s.l.)	Ant. height:	220.5m / 210.5m (a.s.l.)
Ant. gain:	42.8dB / 42.8 dB	Ant. gain:	42.8dB / 42.8 dB
Feeder loss:	1.2dB / 1.6 dB	Feeder loss:	1.6dB / 1.0 dB
Radio:	NL141 . 7.7 GHz - 34 Mb/s	Distance:	58.7 km
Transmitter power:	+26.0 dBm	Path type:	over large bodies of water
Branching loss:	1.2 dB	PL-factor:	5.0 %
Receiver threshold:	-82.0 dBm (1E-3)	System:	2+0
Receiver threshold:	-78.0 dBm (1E-6)		
Signature factor:	0.55 (1E-3)		
Signature factor:	0.69 (1E-6)		

Receiver level: -38.3 dBm
Frequency diversity: none
Space diversity; 10.0m spacing

BER > 1E-3:		BER > 1E-6:	
Fading margin:	43.7 dB	Fading margin:	39.7 dB
Flat fading, no diversity:	0.002105%	Flat fading, no diversity:	0.005288%
Selective fading, no div.	0.003521%	Selective fading, no div.	0.004417%
Flat fading, with diversity:	0.000003%	Flat fading, with diversity:	0.000020%
Selective fading, with div.	0.000005%	Selective fading, with div.	0.000017%
Total:	0.000009%	Total:	0.000037%

9.2.2.1 Dipology

Just out of curiosity Nera in 1994 performed some measurements on selective fading on a 81 kilometre path in Norway using a 64 QAM radio with a channel bandwidth of 30 MHz. The purpose of the measurements was to gain more knowledge of the phenomenology of selective fading. Questions about occurrence of selective fading and notch(dip) dynamics were raised, and the measurements were quite revealing. During the measurement period, which lasted for four summer-months, there were about half a hundred of selective fading events.

9.2.2.1.1 Model

The shape of the selective fades is relatively good described in the literature [15]. The most common description is the three ray model.

70) $$H(\omega) = a\left| 1 - b\,e^{\pm j2\pi(f-f_0)\tau} \right|$$

The channel transfer function is described by the four parameters a, b, f_0 and τ. The a describes the flat part of the fade and b the selective part. f_0 gives the centre-frequency for the notch and τ the delay of the fastest moving reflected ray.

All the measured selective fading events fitted nicely into this three ray model (Well, nearly anything fits into such a description anyhow since there are so many parameters that can be adjusted). In figure 38 some of the events are given together with the model where a, b, f_0 and τ parameters have been made to fit.

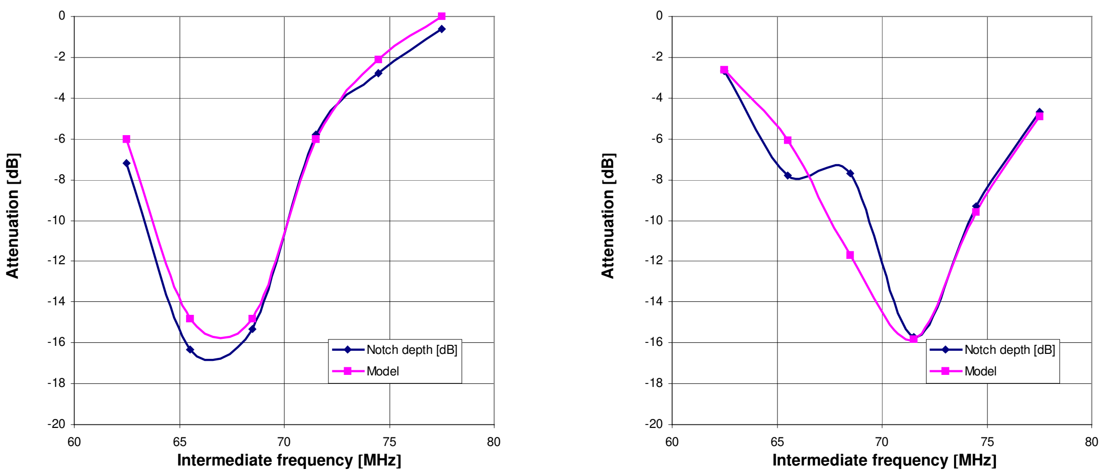
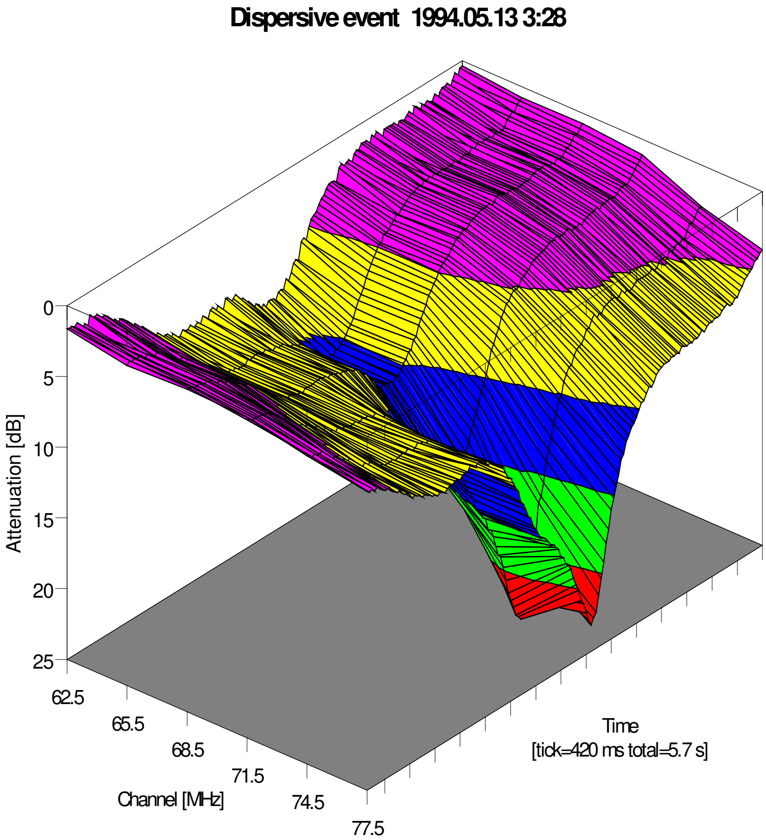


Figure 38 Typical frequency selective fading events.

Average time delay ~ 18 ns.

9.2.2.1.2 Mean delay

The events also showed that most of the notches are outside the measured spectrum. Out of 27 distinguished events only 8 were within the measured spectrum of 15 MHz. Based on this we can estimate a mean notch delay during selective fade events of $\frac{1}{\left((27/8)\cdot 0.015\right)} = 20$ ns or less (rather less since in-band notches are more prominent and give higher in-band distortion).



9.2.2.1.3 Notches vs. input level

All the selective events were highly detectable by observing the channel input level only. A selective event gave a rapid decrease in the input level. The reason being that the notch delays are small compared to the width of the measured channel.

9.2.2.1.4 Dip dynamics

The most noticeable for all of the events is the lack of notch speed. It seems that the most likely selective fading event, is to have a notch growing on a frequency and then disappear again without any noticeable variation in notch frequency f_0. For these few events where f_0 vary, it varies from a couple of MHz/s to less than 15 MHz/s. The events vary in duration from 0.1 seconds to 8.7 seconds with an average of 3.3 seconds duration.

Chapter

10

Diversity

A principal method of overcoming the effects of multipath fading is to use a form of diversity transmission and/or reception. The common forms of diversity in LOS links are **frequency** and **space**, or combinations of both. More recent studies introduce **angle** diversity as an alternative.

10.1 Basic concept of diversity protection

Several diversity protection techniques are available to reduce the impacts of multipath fading on the performance of radio transmission systems. The frequency diversity protection technique takes advantage of the very nature of the frequency selectivity of the multipath dispersive fading. Placing two antennas vertically separated at the receiver tower so only one of the antennas is located in a power minimum, gives a space diversity improvement. The angle diversity technique is based on the slightly different angles of arrival of the indirect delayed waves and the direct wave.

10.1.1 Diversity improvement

An economic advantage of radio transmission systems is that the transmission medium, the atmosphere, is free. However, the free open transmission medium exposes the transmission performance to several radio propagation impairments due to atmospheric anomalies.

An example of fading behaviour for the regular and protection channel is shown in the upper part of figure 39. The two channels are only partially correlated, and the outage time may be considerably reduced by always selecting the better of the two channels. The diversity improvement factor is illustrated in the lower part of figure 39.

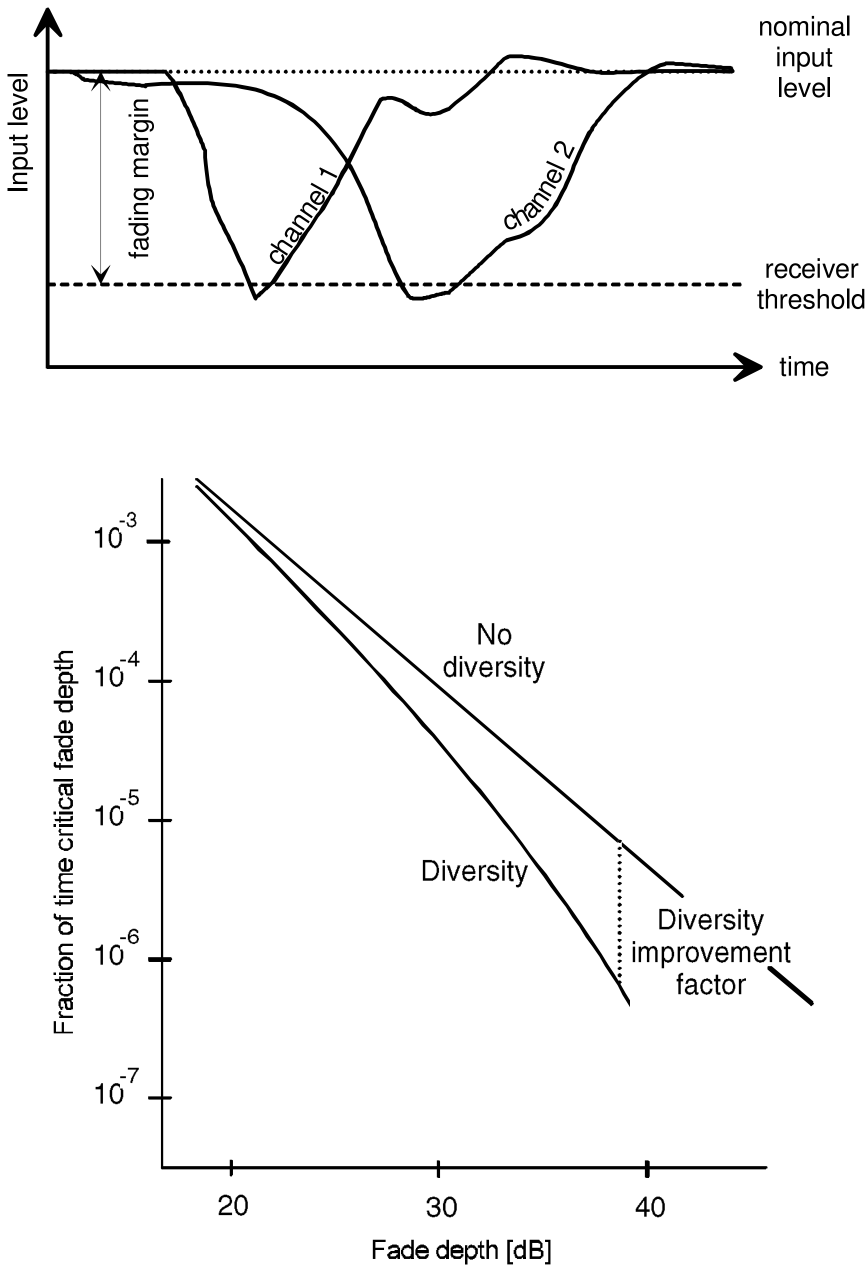


Figure 39 Diversity improvement

By switching or combining the different channels carrying the same signal, it is possible to attain an improvement relative to a single channel given by the factor:

71) $$I = \frac{P_{\text{Single channel}}}{P_{\text{Diversity}}}$$

The diversity improvement factor for digital systems is defined by the ratio of the exceedance times for a given BER with and without diversity. A prediction procedure for the diversity improvement factor can be found in the ITU-R recommendation P.530 [31].

10.2 Single diversity

For a diversity scheme employing one additional channel, the methods described in ITU-R report 338-6 [18] and recommendation P530 [31] can be used to calculate the improvement factor for different diversity arrangements.

10.2.1 Space diversity

10.2.1.1 Diversity techniques in analogue systems

The system performance may be significantly improved by use of space diversity. Identical information is transmitted over separate paths. Whenever space diversity is used, angle diversity should also be employed by tilting the antennas at different upward angles.

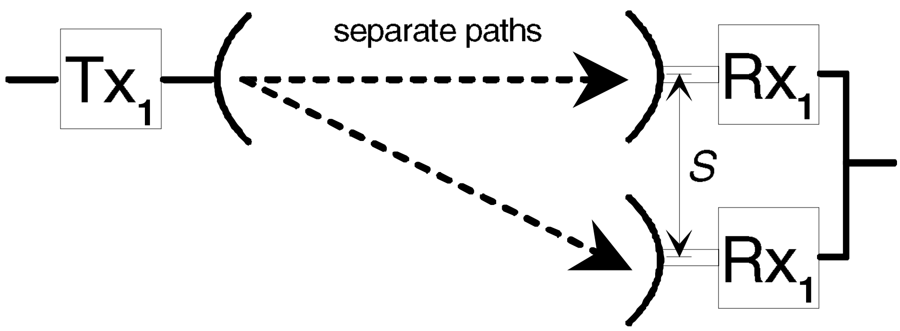


Figure 40 Space diversity principle.

The space diversity improvement factor on overland paths can be estimated from

72) $$I_{sd} = \left[1 - \exp\left(-3.34 \cdot 10^{-4} \cdot S^{0.87} \cdot f^{-0.12} \cdot d^{0.48} \cdot \left(\frac{P_0}{100}\right)^{-1.04}\right)\right] \cdot 10^{(F-V)/10}$$

where

d - path length (km)

F - fade depth (dB) for the unprotected path

f - frequency (GHz)

G_{S1}, G_{S2} - gains of the two space diversity antennas (dB)

P_0 - fading occurrence factor

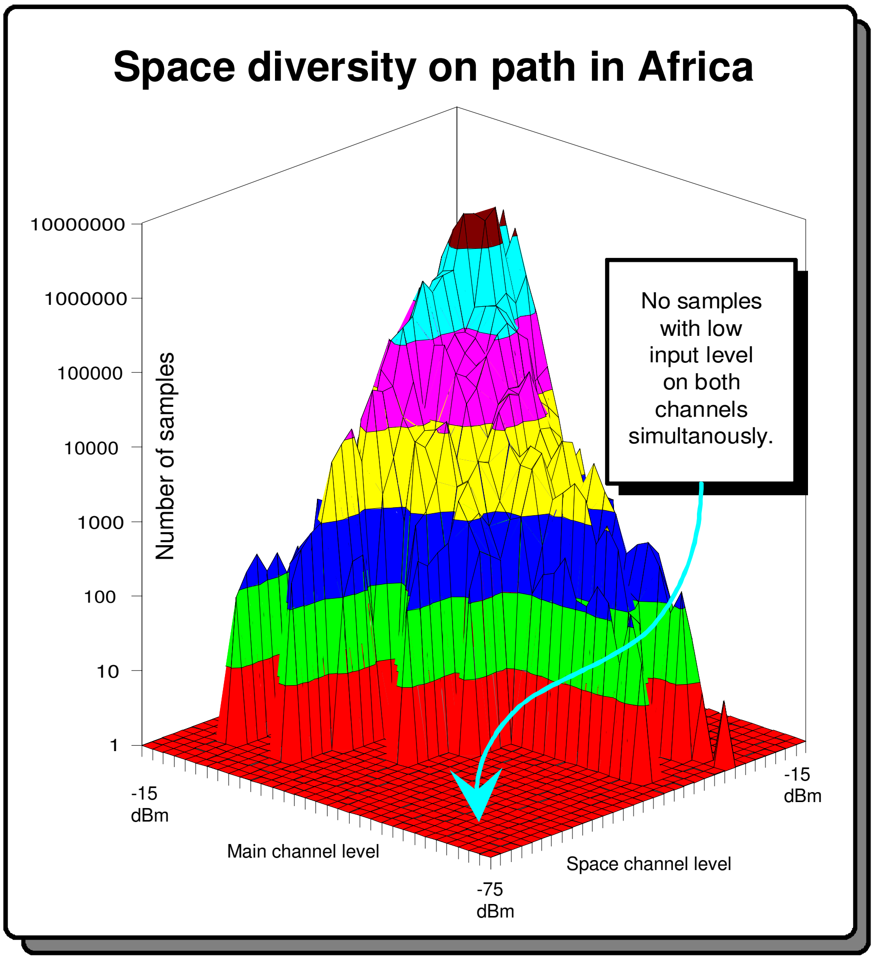
S - vertical separation (centre-to-centre) of receiving antennas (m)

$$V = |G_{s1} - G_{s2}|$$

The relation for I_{sd} applies only when the following conditions are met:

$$2 \text{ GHz} \leq f \leq 11 \text{ GHz}$$
$$43 \text{ km} \leq d \leq 240 \text{ km}$$
$$3 \text{ m} \leq S \leq 23 \text{ m}$$

ITU-R Rep. 338-6 [18] indicates that 72) can be used with reasonable accuracy for path lengths down to 25 km. In cases where any of these boundaries have been exceeded (within reasonable limits), the parameters may be set equal to the boundary value. E.g. for 13 or 15 GHz links, the improvement factor for 11 GHz can be calculated.



10.2.1.2 Diversity techniques in digital systems

In space diversity systems, maximum-power combiners have been used most widely so far. The step-by-step procedure given below applies to systems employing such a combiner. Other combiners, employing a more sophisticated approach using both minimum-distortion and maximum-power dependent on a radio channel evaluation may give somewhat better performance.

Step 1: Calculate the multipath activity factor η, using equation 66).

Step 2: Calculate the square of the non-selective correlation coefficient, k_{ns}, from:

73) $$k_{ns}^2 = 1 - \frac{I_{sd} \cdot P_{flat}}{\eta}$$

where the improvement, I_{sd}, can be evaluated from equation 72) for a flat fade depth F (dB) and P_{flat} from equation 52).

Step 3: Calculate the square of the selective correlation coefficient, k_s, from:

74)
$$k_s^2 = \begin{cases} 0.8238 & \text{for} \quad r_w \le 0.5 \\ 1 - 0.195\,(1 - r_w)^{0.109 - 0.13\log(1 - r_w)} & \text{for} \quad 0.5 < r_w \le 0.9628 \\ 1 - 0.3957\,(1 - r_w)^{0.5136} & \text{for} \quad r_w > 0.9628 \end{cases}$$

where the correlation coefficient, r_w, of the relative amplitudes is given by:

75)
$$r_w = \begin{cases} 1 - 0.9746\left(1 - k_{ns}^2\right)^{2.170} & \text{for} \quad k_{ns}^2 \le 0.26 \\ 1 - 0.6921\left(1 - k_{ns}^2\right)^{1.034} & \text{for} \quad k_{ns}^2 > 0.26 \end{cases}$$

Step 4: Calculate the non-selective outage probability, P_{dns}, from:

76)
$$P_{dns} = \frac{P_{flat}}{I_{sd}}$$

where P_{flat} is the non-protected outage given by equation 52).

Step 5: Calculate the selective outage probability, P_{ds}, from:

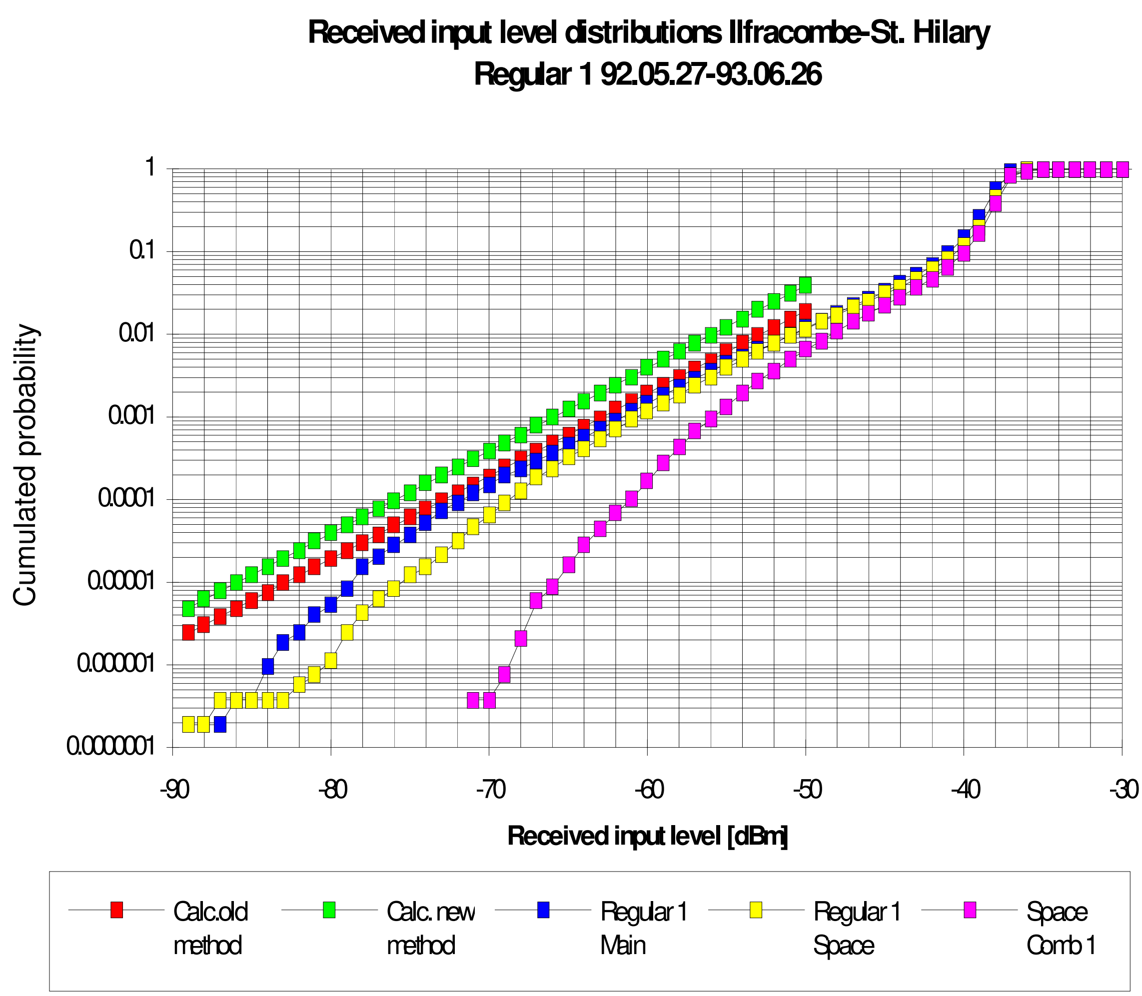
77)
$$P_{ds} = \frac{P_{sel}^2}{\eta \cdot \left(1 - k_s^2\right)}$$

where P_{sel} is the non-protected outage given by equation 65).

Step 6: Calculate the total outage probability, P_d, as follows:

78)
$$P_d = \left(P_{ds}{}^{0.75} + P_{dns}{}^{0.75}\right)^{1.33}$$

The Bristol channel path



The above graph can be compared with figure 39 where "Regular 1 main" and "Regular 1 space" represent the "No diversity" curve and "Space Comb 1" represents the "Diversity" curve. The diversity improvement factor is > 100 at threshold level for this particular month.

10.2.2 Frequency diversity

Frequency diversity is a cost-effective technique that provides equipment protection as well as protection from multipath fading. From a spectrum efficiency point of view, the technique is not recommendable for 1+1 systems where only 50% of the spectrum is utilised. For n+1 systems where n>1, the spectrum efficiency is better, and a good protection is achieved with a relatively low extra cost and efficient spectrum utilisation.

For co-channel systems, a n+2 switching system is normally used as both traffic channels operating at the same radio frequency are switched simultaneously.

10.2.2.1 Redundant 1+1 system

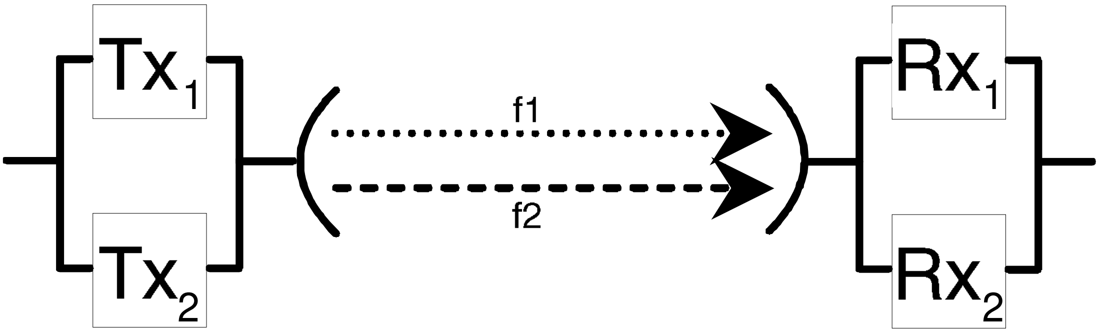


Figure 41 Frequency diversity principle.

79) $$I_{fd} = \frac{80}{f \cdot d} \cdot \frac{\Delta f}{f} \cdot 10^{\frac{F}{10}} \qquad \{I_{fd} \geq 5\}$$

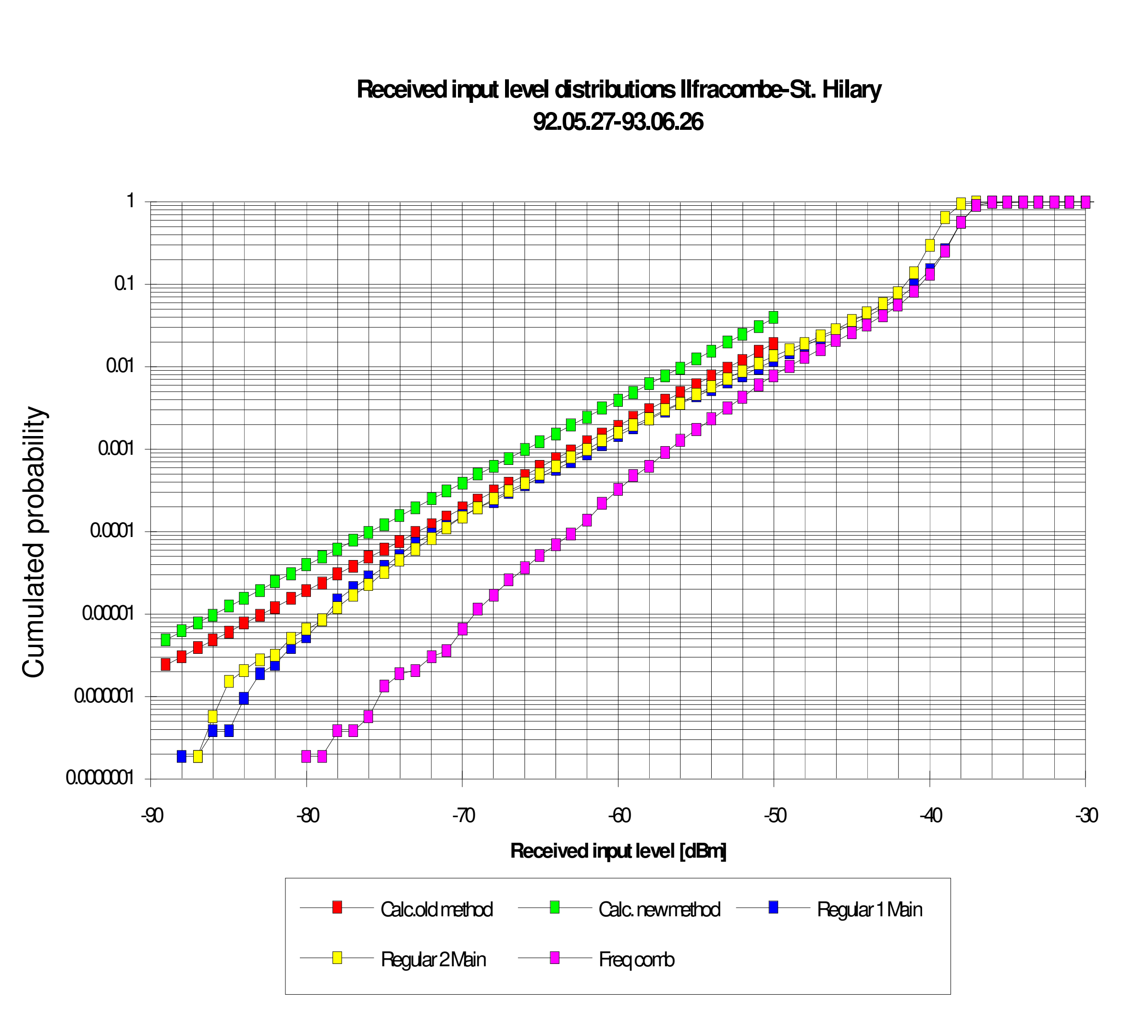
Δ_f - frequency spacing between rf-channels in GHz

The equation is considered valid only for values of $I_{fd} \geq 5$. The relation for I_{fd} applies only when the following conditions are met:

$$2\text{ GHz} \leq f \leq 11\text{ GHz}$$
$$30\text{ km} \leq d \leq 70\text{ km}$$
$$\Delta_f / f \leq 0.05$$

In cases where these boundaries are exceeded (within reasonable limits), the I_{fd} is calculated with boundary values. E.g. if the distance is 15 km, then I_{fd} is calculated with $d = 30$ km.

The Bristol channel path



10.2.2.2 Redundant N+1 system

If frequency diversity is used in n+1 operation, n>1, the diversity improvement factor will be reduced since there are more than one channel sharing the same diversity channel.

If it is assumed that no more than two of the RF-channels are simultaneously afflicted by equal fading, and both have the same priority, the reduced diversity improvement factors are given by:

80)
$$I_{fd\,\{2+1\}} = 0.67 \cdot I_{fd} \qquad I_{fd\,\{5+1\}} = 0.49 \cdot I_{fd}$$
$$I_{fd\,\{3+1\}} = 0.57 \cdot I_{fd} \qquad I_{fd\,\{6+1\}} = 0.47 \cdot I_{fd}$$
$$I_{fd\,\{4+1\}} = 0.52 \cdot I_{fd} \qquad I_{fd\,\{7+1\}} = 0.45 \cdot I_{fd}$$

10.2.2.3 Switching sections

The frequency diversity improvement factor is reduced if there are more than one path between switching sections.

The reduction of the improvement factor for a path is given by

81) $$I_{fd\{\text{sw.sect.}\}} = \frac{I_{fd}}{1 + (\text{sw.sect.} - 1) \cdot \frac{P_{path}}{100} \cdot I_{fd}}$$

sw. sect. - number of paths between switching sections.

P_{path} - path outage (in percent) including space diversity improvement if used.

10.2.3 Hot standby configuration

The hot standby configuration is often used to give equipment diversity (protection) on paths where propagation conditions are non-critical to system performance. This configuration gives no improvement of system performance, but reduces the system outage due to equipment failures.

The transmitters and receivers in figure 42 operate at the same frequency. Consequently no frequency diversity improvement could be expected.

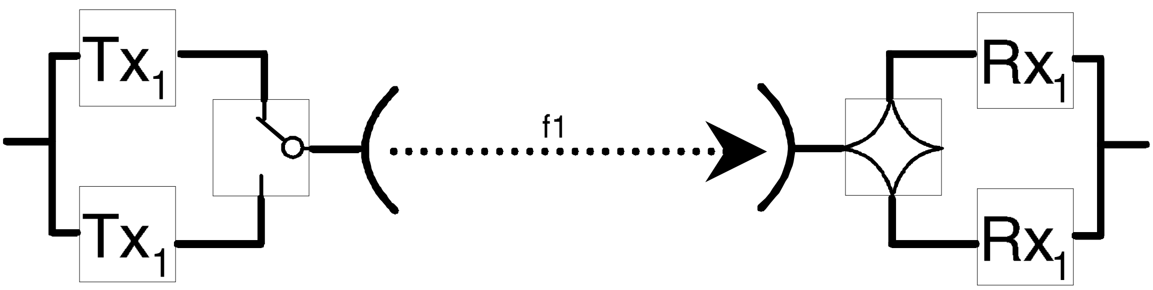


Figure 42 Hot standby principle.

10.2.4 Hybrid diversity

Hybrid diversity is an arrangement where a 1+1 system has two antennas at one of the radio sites. Such a system will in effect act as a space diversity system and formula 72) is used to calculate the diversity improvement factor.

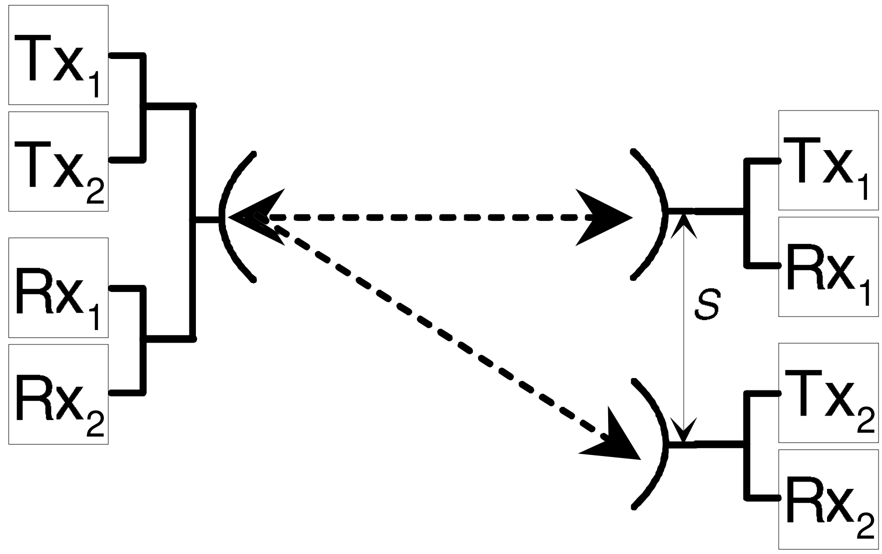


Figure 43 Hybrid diversity principle (both directions).

10.3 Angle diversity

Multipath fading in L.O.S. microwave links has emerged as the predominant factor affecting the performance of digital transmission systems. The mechanism is indicated in figure 44, showing reflected rays for a typical path. The angle diversity has been introduced as an efficient diversity technique that can discriminate against multipath signals. The principle of angle diversity is shown in figure 45. The two antenna feed-horns are tilted slightly off the boresight, giving a dual beam parabolic dish antenna as shown.

Angle diversity techniques are based upon differing angles of arrival of radio signals at a receiving antenna, when the signals are a result of multipath propagation. The simplest form of angle diversity technique used involves a receiving antenna with its vertical pattern tilted purposely off the boresight line, such that a direct-path signal is received at a level approximately 2 to 3 dB down from maximum gain. Thus, a form of diversity reception is possible, whenever the off-boresight antenna can provide a better signal to the radio than the antenna aligned on the boresight. The technique is applicable to a radio system using either IF signal combining or a switched form of receiver selection.

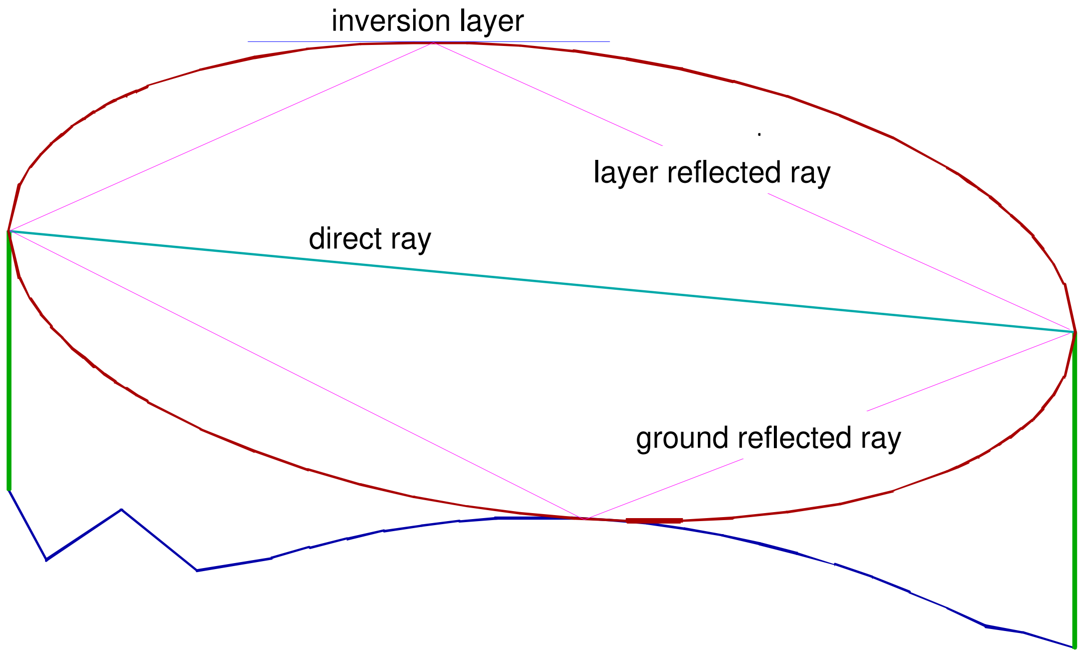


Figure 44 Reflective rays in test path.

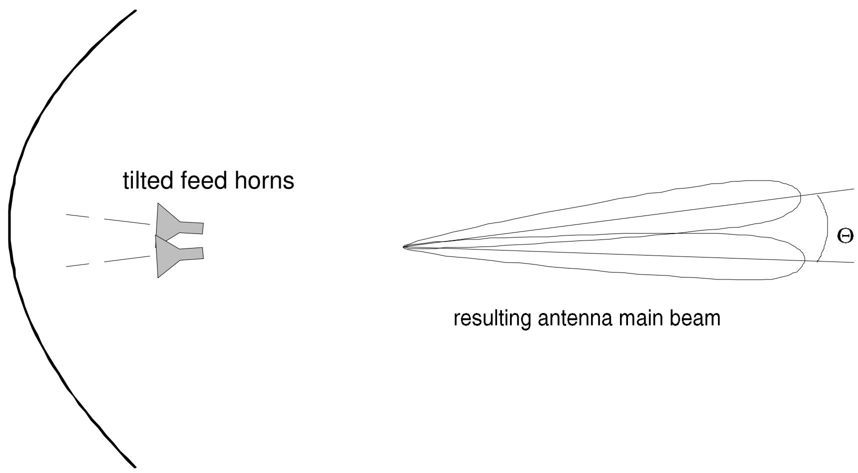


Figure 45 Principle of angle diversity antenna.

Because of the different angles of arrival, the multipath components add up in a different way for the different beams, resulting in almost non-correlated fading in the diversity branches. It was generally found that the beams pointing towards the ground experienced deeper fading at a single frequency for a given time percentage than those pointing upwards.

The angle diversity improvement factor is found to be in the same order as the space diversity improvement factor for most of the paths investigated in the papers found in the reference list [22-23].

10.3.1 Prediction of outage using angle diversity

Step 1: Estimate the average angle of arrival, $\mu\theta$, from:

82) $$\mu_\theta = 2.89 \times 10^{-5}\ G_m\ d \qquad \text{degrees}$$

where G_m is the average value of the refractivity gradient (N-unit/km) and d is the distance in km. When a strong ground reflection is clearly present, μ_θ can be estimated from the angle of arrival of the reflected ray in standard propagation conditions.

Step 2: Calculate the non-selective reduction parameter, r, from:

83) $$r = \begin{cases} 0.113\ \sin\left[150(\delta / \Omega) + 30\right] + 0.963 & \text{for } q > 1 \\ q & \text{for } q \le 1 \end{cases}$$

where:

84) $$q = 2505 \times 0.0437^{(\delta/\Omega)} \times 0.593^{(\varepsilon/\delta)}$$

and:

- δ: angular separation between the two patterns
- ε: elevation angle of the upper antenna (positive towards ground)
- Ω: half-power beam width of the antenna patterns.

Step 3: Calculate the non-selective correlation parameter, Q_0, from:

85)
$$Q_0 = r \left(0.9399^{\mu_\theta} \times 10^{-24.58\,\mu_\theta^2}\right) \left| 2.469^{1.879^{(\delta/\Omega)}} \times 3.615^{\left[(\delta/\Omega)^{1.978}\ (\varepsilon/\delta)\right]} \times 4.601^{\left[(\delta/\Omega)^{2.152}\ (\varepsilon/\delta)^2\right]} \right|$$

Step 4: Calculate the multipath activity factor η, using equation 66).

Step 5: Calculate the non-selective outage probability from:

86) $$P_{dns} = \eta\ Q_0 \times 10^{-\frac{F}{6.6}}$$

Step 6: Calculate the square of the selective correlation coefficient, k_s, from:

87)

$$k_s^2 = 1 - |\, 0.0763 \times 0.694^{\mu_\theta} \times 10^{23.3\,\mu_\theta^2} \,|\, \delta \left(0.211 - 0.188\ \mu_\theta - 0.638\ \mu_\theta^2 \right)^{\Omega}$$

Step 7: The selective outage probability, P_{ds}, is found from:

88)

$$P_{ds} = \frac{P_s^2}{\eta\left(1 - k_s^2\right)}$$

where P_s is the non-protected outage (see Step 3).

Step 8: Finally, calculate the total outage probability, P_d, from:

89)

$$P_d = \left(P_{ds}{}^{0.75} + P_{dns}{}^{0.75} \right)^{1.33}$$

10.4 Combined diversity

In many practical configurations a combination of frequency techniques is used, in particular the combination of space- and frequency diversity. Different combination algorithms exist, but Nera has chosen to apply a conservative method by using the following simple formula to calculate the improvement factor for combined diversity configuration:

90)

$$I = I_{sd} + I_{fd}$$

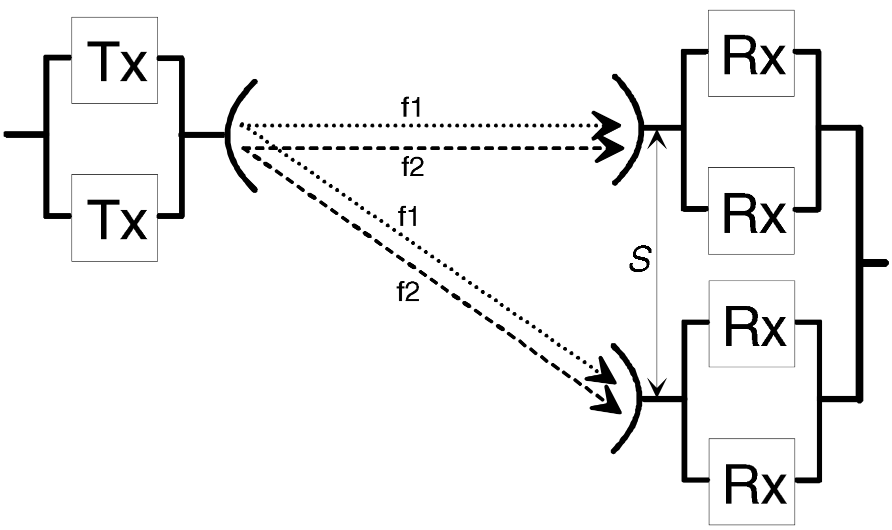
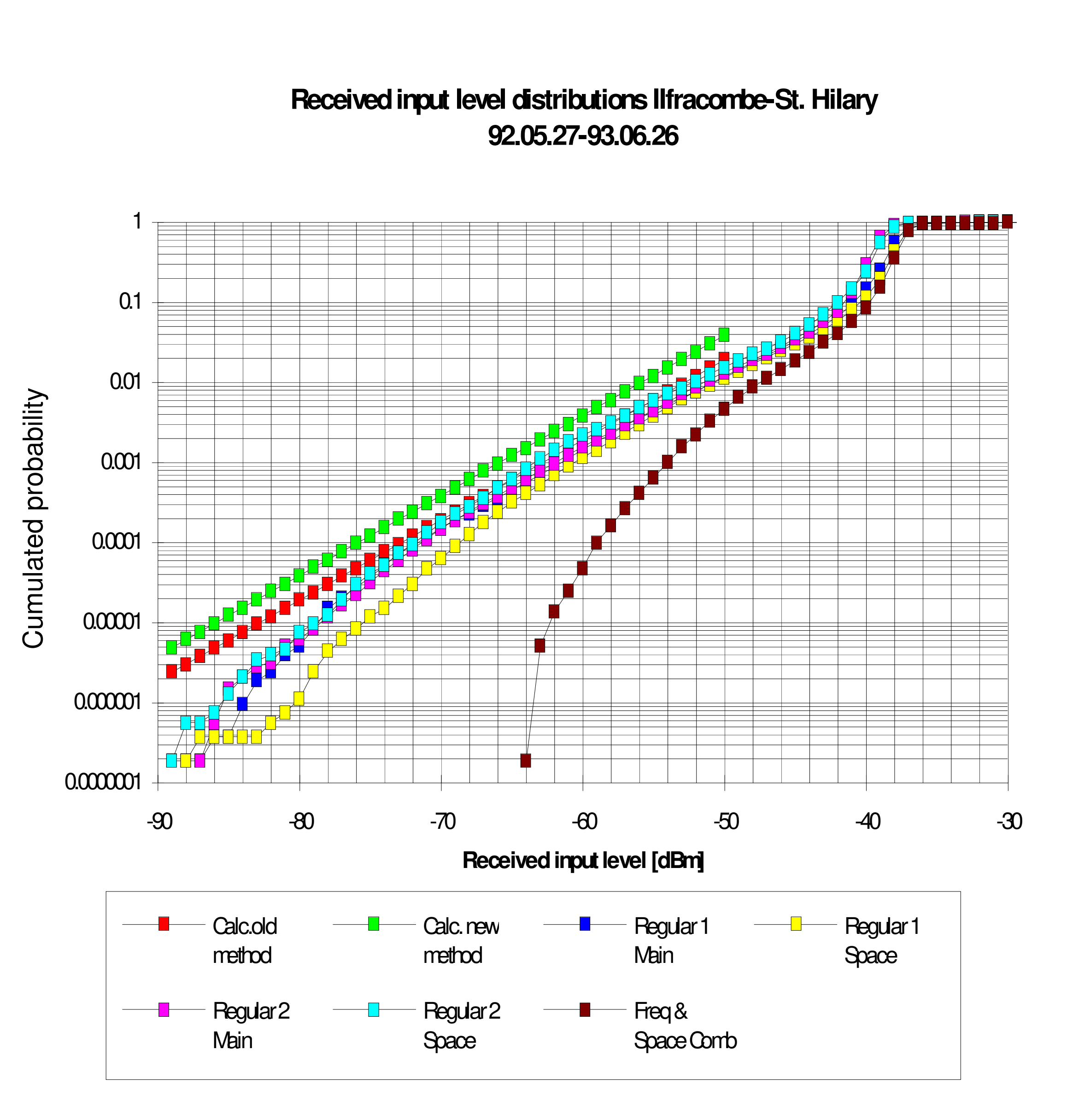


Figure 46 Combined space and frequency diversity

The Bristol channel path



10.5 Path diversity

The previously covered diversity techniques are powerful countermeasures to multipath fading. Outage due to precipitation will not be reduced by use of frequency-, angle- or space diversity. Rain attenuation is mainly a limiting factor at frequencies above ~10 GHz. Systems operating at these high frequencies are often used in urban areas where the radio relay network may form a mix of star and mesh configuration as indicated in figure 47.

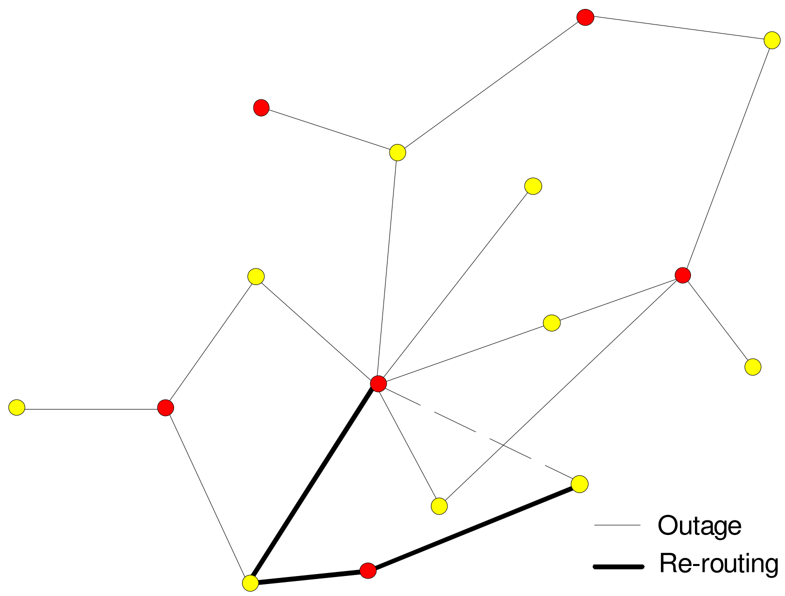


Figure 47 Star-mesh network configuration

The area covered by an intense shower is normally much smaller than the coverage of the entire network. Re-routing of the signal via other paths will therefore be a useful counter-measure to outage due to rain.

Changes to the ITU-R recommendations and models are happening relatively frequently, and attention to new and revised documents from the ITU is therefore required to keep up with these revisions. Consequently, regular use of the ITU homepage can be recommended.

Chapter

11

Cross-polar interference

Co-channel operation of radio relay systems is the answer to the market's demand for increased capacity and more efficient spectrum utilisation. As spectrum pricing has become more and more common, the interest for co-channel systems has grown, and in the near future it is likely that these systems will appear both in the trunk and access net.

With the use of co-channel systems the capacity can be doubled compared to conventional radio relay systems. In co-channel systems transmission of two separate traffic channels is performed on the same radio frequency but on orthogonal polarizations. This works well as long as the discrimination between the two polarizations called Cross Polar Discrimination (XPD), is sufficient to ensure interference-free operation. The nominal value of XPD is termed XPD_0 and is governed by the cross-polarization patterns of the antennas. The value is usually in the range 30-40 dB.

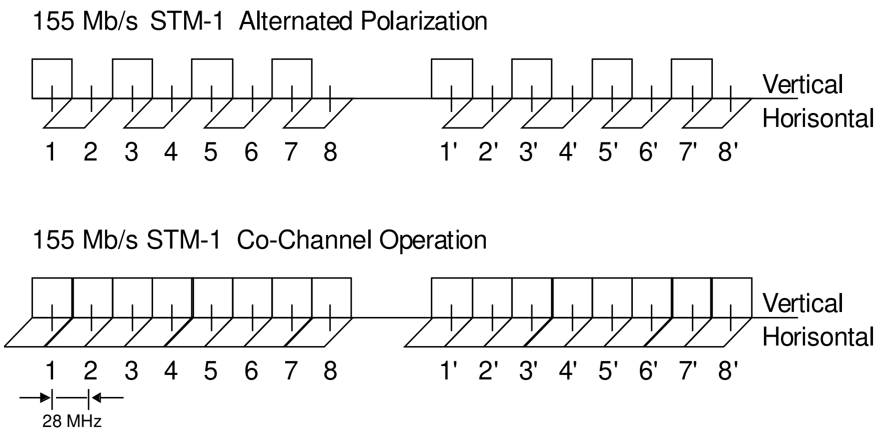


Figure 48 Frequency plan for co-channel system

The amount of XPD varies with time. Both multipath- and rainfading can result in severe degradation of the XPD level. As the XPD decreases the interference level in the channel will rise and may cause threshold degradation and errors in the data traffic. In order to make the radio relay systems resistant to the variation in XPD, most manufacturers have included Cross Polar Interference Cancellers (XPIC) in the receiver. These XPICs remove the unwanted signal that has leaked from the opposite polarization into the wanted one. With an XPIC the XPD can be as low as 15-20 dB before the performance is degraded.

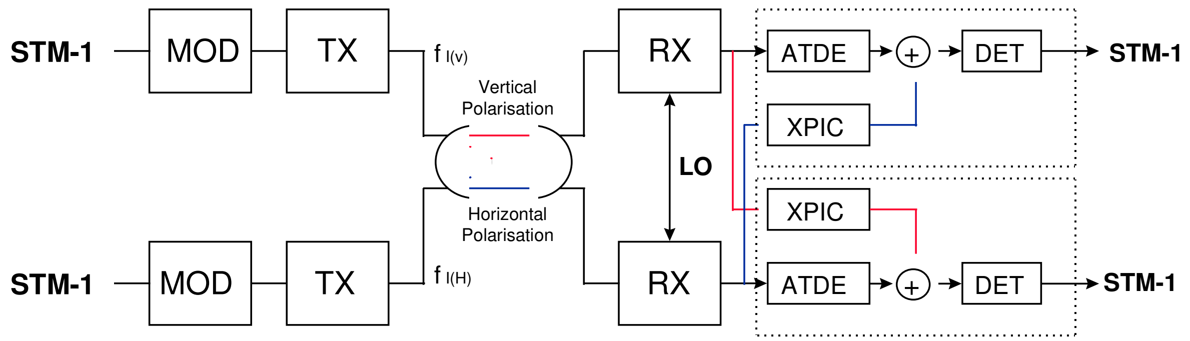


Figure 49 Principle of XPIC (Cross Polar Interference Canceller)

11.1 Quantitative description

The Cross-polarization Interference (XPI) is defined by

91) $$XPI = 20 \cdot \log \frac{E_{11}}{E_{21}} \quad [\mathrm{dB}]$$

where E_{11} and E_{21} are given in figure 50.

Propagation measurements usually give the Cross-polarization Discrimination (XPD) defined by

92) $$XPD = 20 \cdot \log \frac{E_{11}}{E_{12}} \quad [\mathrm{dB}]$$

where E_{11} and E_{12} are given in figure 50.

In most cases *XPI* and *XPD* are identical.

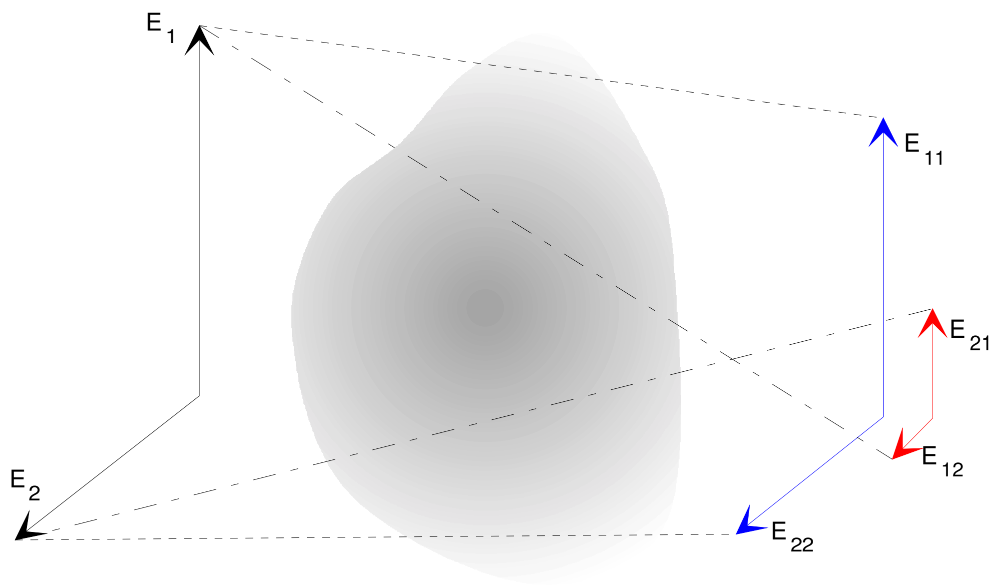


Figure 50 Dual polarised system suffering from XPI

11.2 Outage due to clear air effects

During multipath fading not only the input level, but also the amount of XPD will vary. The figure below shows measurements performed on a 130 kilometre path in Switzerland, and indicates a dB to dB relation between fading depth and the amount of XPD. The figure also indicates that for this particular path, which is very long, the amount of outage due to XPD will be higher than the amount due to multipath alone.

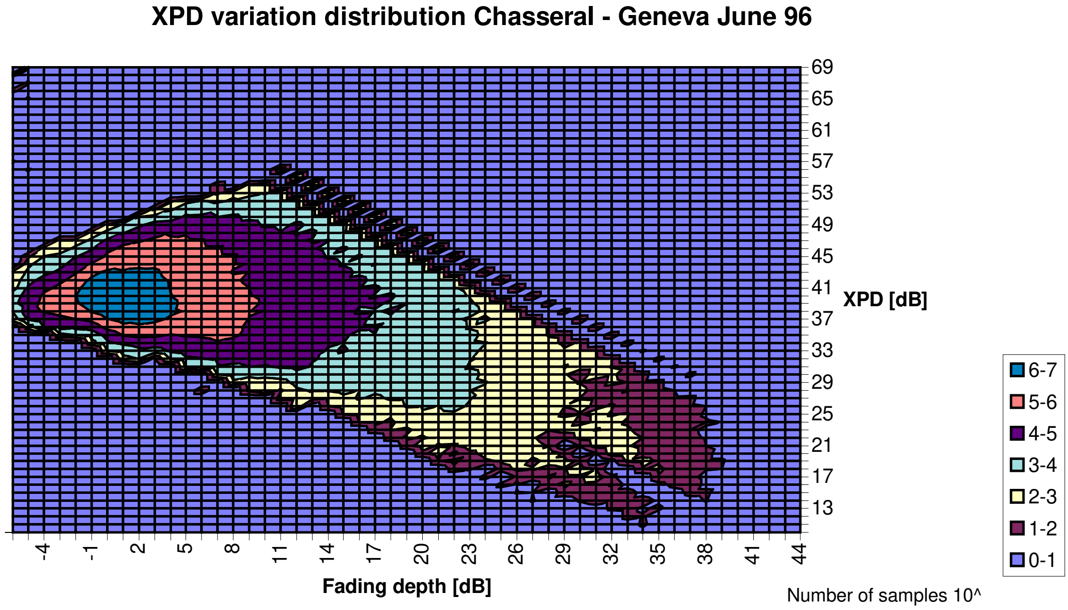


Figure 51 XPI variations as a function of fading depth

The depolarization mechanisms that involve the propagation medium are:

* Depolarization of a reflected component of the co-polarised signal due to scattering or reflection from land or water surfaces.

* Depolarization of a reflected component of the co-polarised signal due to reflection from an atmospheric layer.

* Depolarization of a direct component of the signal due to refractive bending in the atmosphere.

* Depolarization of the direct co-polarised signal by tropospherical turbulence.

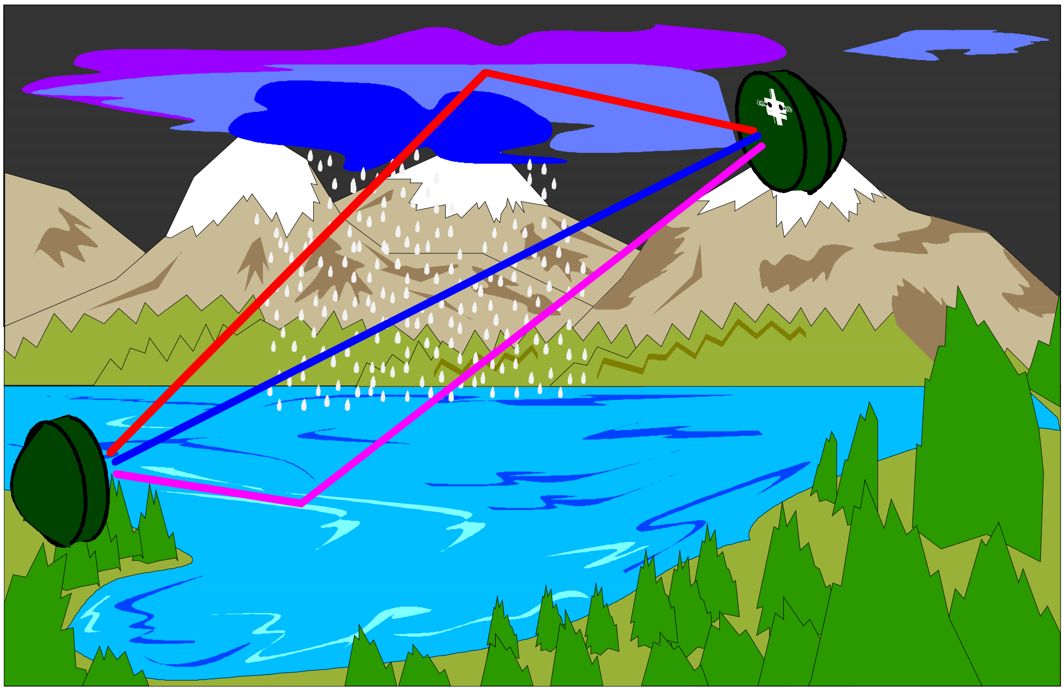


Figure 52 Depolarization mechanisms.

As indicated in figure 52, the reflected signals reach the receiving antenna at an offset angle referred to the main beam of the antenna. In addition to the depolarization in the medium itself, reflected signals are coupled to the cross-polar receiver via the cross-polarised antenna pattern. The cross-polarization discrimination (XPD) of the antenna is a function of this offset angle as shown in figure 53. Consequently reflected signals from surfaces and/or atmospheric layers may cause additional coupling to the orthogonal polarization due to reduced antenna XPD for the angle of incidence.

All of the mechanisms mentioned above could occur during multipath fading. It is expected, however, that one or two would predominate during severe reductions in the XPD of the system.

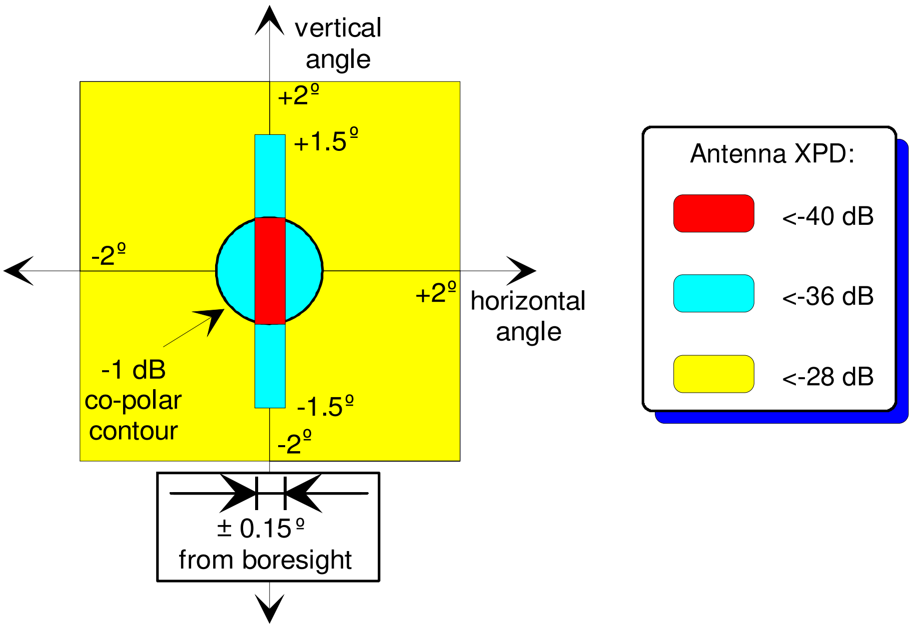


Figure 53 Antenna cross-polarization discrimination

11.2.1 A step-by-step procedure for predicting outage

In ITU-R recommendation P.530-7 a step-by-step procedure for predicting the outage due to clear-effects is given. It starts by calculating the XPD_0 based on the XPD_g, which is the manufacturer's guaranteed minimum XPD at boresight for both the transmitting and receiving antennas. The formula takes into account that the typical value for an antenna is usually better than what is guaranteed and the fact that an XPD of more than 40 dB is hard to achieve.

93) $$XPD_0 = \begin{cases} XPD_g + 5 & for\, XPD_g \leq 35 \\ 40 & for\, XPD_g > 35 \end{cases}$$

Since the variation in XPD is correlated to the multipath activity the fading activity factor is used to scale the probability of outage due to cross-polarization, P_{xp}. The fading activity factor η is related to the fading occurrence factor P_0. (Refer to equation 57 in chapter 9.)

94) $$\eta = 1 - e^{-0.2(\frac{P_0}{100})^{3/4}}$$

The next parameter to establish is Q that is given by

95) $$Q = -10\log\left|\frac{k_{xp}\eta}{P_0}\right|$$

where

96) $$k_{xp} = \begin{cases} 0.7 & \text{one transmit antenna} \\ 1 - 0.3\exp\left[-4\cdot 10^{-6}\left|\frac{s_t}{\lambda}\right|^2\right] & \text{two transmit antennas} \end{cases}$$

In the case where the two orthogonally polarized transmissions are from different antennas, the vertical separation is s_t [m], and the carrier wavelength is λ [m].

The probability of outage P_{xp} due to clear-air cross-polarization is given by

97) $$P_{xp} = P_0 \cdot 10^{-\frac{M_{XPD}}{10}}$$

where M_{XPD}(dB) is the equivalent XPD margin for a reference BER given by

98) $$M_{XPD} = \begin{cases} C - \frac{C_0}{I} & \text{without XPIC} \\ C - \frac{C_0}{I} + XPIF & \text{with XPIC} \end{cases}$$

Here C_0/I is the carrier to interference ratio for a reference BER, which can be evaluated, either from simulations or from measurements. The C parameter is determined using

99) $$C = XPD_0 + Q$$

XPIF is the laboratory-measured cross-polarization improvement factor that gives the difference in cross-polar isolation XPI at sufficiently large carrier-to-noise ratio (typically 35 dB) and at a specific BER for systems with and without XPIC. Typical values for XPIF are in the range 20-25 dB.

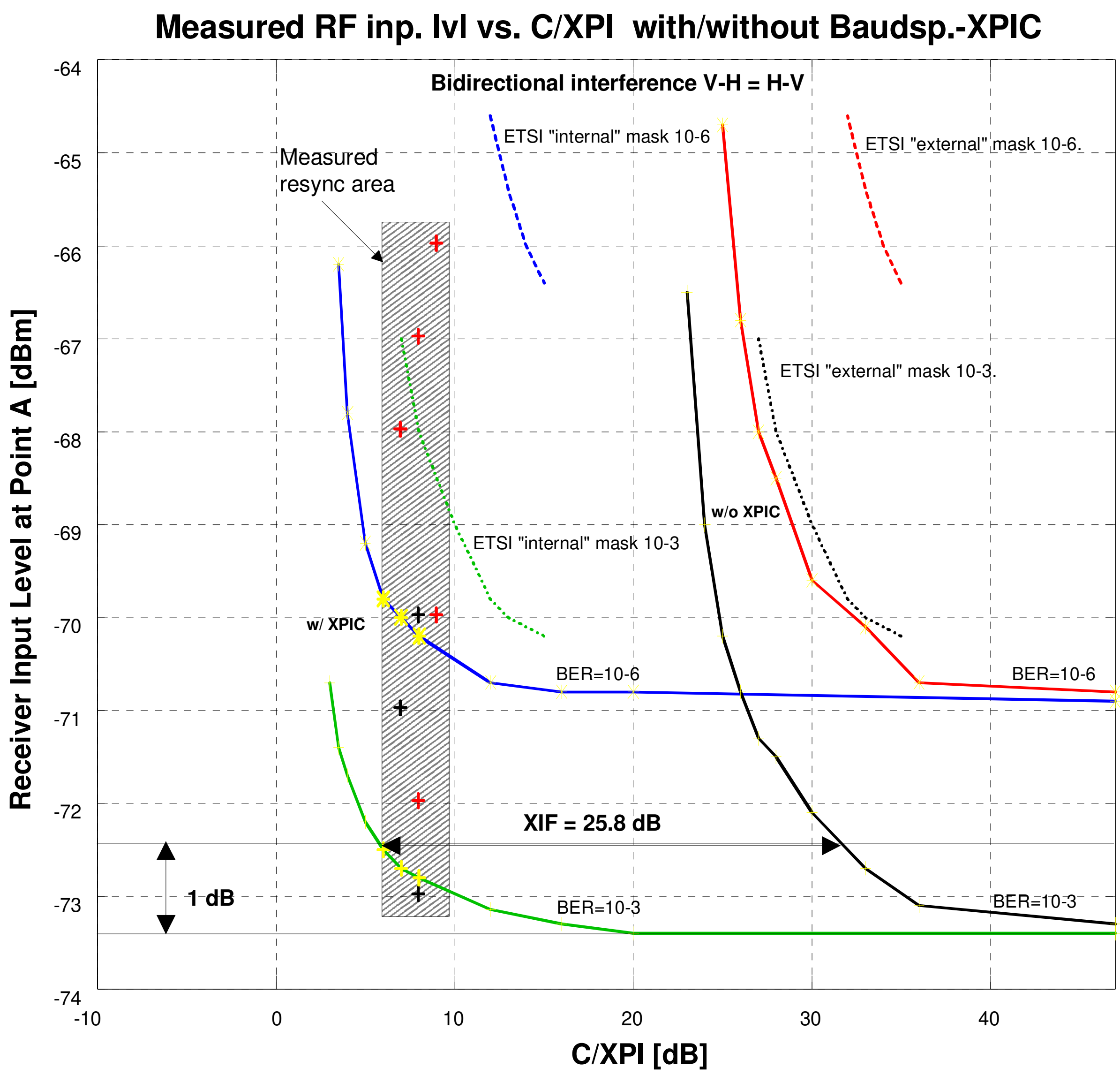


Figure 54 Receiver threshold degradation with XPI

11.2.2 Space diversity improvement

Currently there is no available formula given by the ITU-R for calculating the diversity improvement of XPD by using separate receiving antennas and receivers. However, measurements show that a high degree of improvement on the XPD performance can be achieved by using space diversity. Usually a space diversity system experience highly uncorrelated signals and hence a good XPD can be obtained in the channel having the least fading. The figure shows the XPD diversity performance on the 130 kilometre path in Switzerland. For the threshold XPD, i.e. the lowest allowable XPD value before the onset of errors, which is around 15-20 dB the improvement factor is larger than 100.

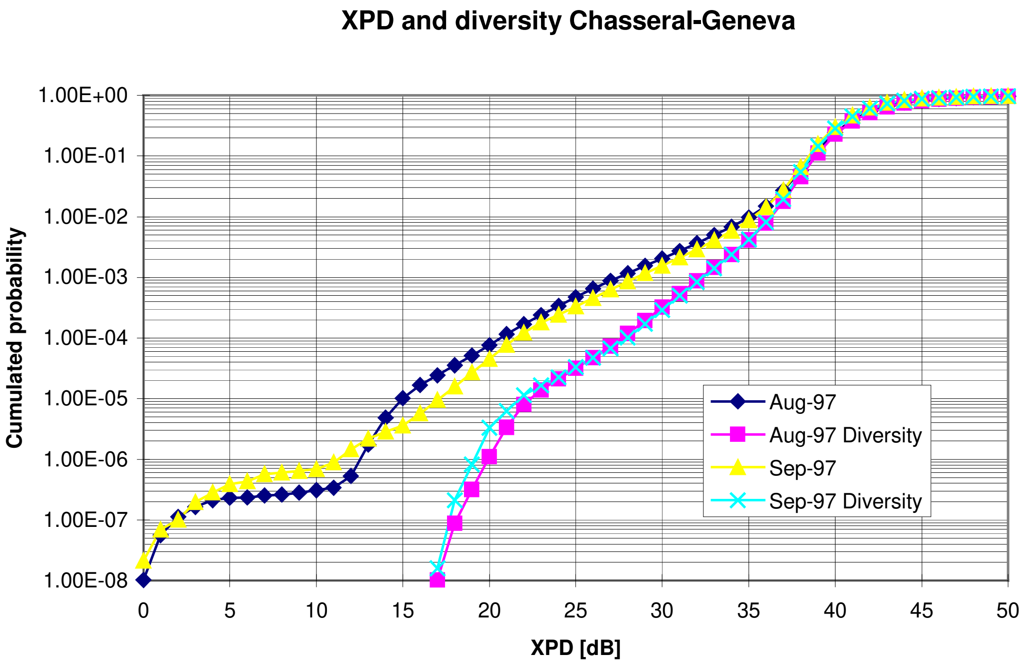


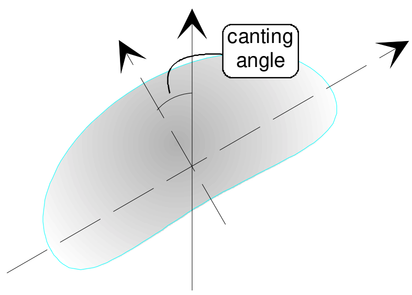
Figure 55 Cumulated XPD probability

11.3 Outage due to precipitation effects

In addition to the usual attenuation of microwave signals due to rain, there will also be a depolarization effect. This depolarization may be substantial even at frequencies where the attenuation is insignificant (below 10 GHz).

Experiments have shown that when raindrops grow large (~3 mm →) they depart from the spherical shape and become anisotropic like an oblate spheroid.

As long as the raindrops fall with their polarization vectors horizontal and vertical, no depolarization occurs. The raindrops may be canted due to vertical wind gradients. Depolarization will occur due to differential attenuation and differential phase shift between the two orthogonal polarizations.



On short paths the depolarization due to rain is larger than that for multipath.

Experiments have shown that paths at low altitudes and paths having large tilts relative to the horizontal are most affected by depolarization.

11.3.1 XPD statistics

Intense rain governs the reductions in XPD observed for small percentages of time. For paths on which more detailed predictions or measurements are not available, a rough estimate of the unconditional distribution of XPD can be obtained from a cumulative distribution of the co-polarised rain attenuation CPA using

100) $$XPD = U - V(f)\cdot\log(CPA) \quad \text{dB}$$

The coefficients U and V(f) are in general dependent on a number of variables and empirical parameters, including frequency, f. For line-of-sight paths with small elevation angles and horizontal or vertical polarization, these coefficients may be approximated by:

101) $$\begin{aligned} &U = U_0 + 30\cdot\log(f) \\ &V(f) = 12.8 f^{0.19} && for\ 8 \le f \le 20\,GHz \\ &V(f) = 22.6 && for\ 20 < f \le 35\,GHz \end{aligned}$$

An average value of U_0 of about 15 dB, with a lower bound of 9 dB for all measurements, has been obtained for attenuation greater than 15 dB. The variability in the values of U and V(f) is such that the difference between the CPA values for vertical and horizontal polarization is not significant when evaluating XPD.

11.3.2 A step-by-step procedure for predicting outage

The first step is to determine the path attenuation exceeded for 0.01% of the time, $A_{0.01}$ by using equation 48) in the precipitation chapter. Then the equivalent path attenuation, A_p (dB) is calculated using

102) $$A_p = 10^{((U - C_0/I + XPIF)/V)}$$

where U and V are obtained from equation 101), C_0/I (dB) is the carrier-to-interference ratio defined for the reference BER without XPIC, and XPIF (dB) is the cross-polarised improvement factor for the reference BER. If an XPIC device is not used, set XPIF = 0.

The next step is to determine the following parameters

103) $m = \begin{cases} 23.26 \cdot \log\left[A_p / (0.12 A_{0.01})\right] & \text{m} \leq 40 \\ 40 & \text{otherwise} \end{cases}$

and

104) $n = \left(-12.7 + \sqrt{161.23 - 4m}\right) / 2$

Valid values for n must be in the range of –3 to 0. Note that in some cases, especially when an XPIC device is used, values of n less than –3 may be obtained. If this is the case, it should be noted that values of *n* less than –3 will give outage BER < 1E –5.

Now the outage probability due to precipitation effect can be calculated using

105) $P_{XPR} = 10^{(n-2)}$

Chapter

12

Interference

12.1 Noise

Reception of signals in telecommunication systems may be marred by noise, which can originate from a variety of sources. Many of these sources are man-made and could, in principle, be eliminated. Fundamental noise sources do however exist, and must be understood to enable proper design of telecommunication equipment.

TYPICAL

$T = 300$ K
$B = 6$ MHz
$P_n = -106$ dBm

12.1.1 Thermal noise

Random motion of electrons due to thermal energy result in an average noise power given by

106) $$P_n = kTB \quad \text{[W]}$$

where k - Boltzmann's constant $\left(k = 1.38 \cdot 10^{-23}\ J/K\right)$
T - temperature in Kelvin
B - bandwidth of noise spectrum [Hz]

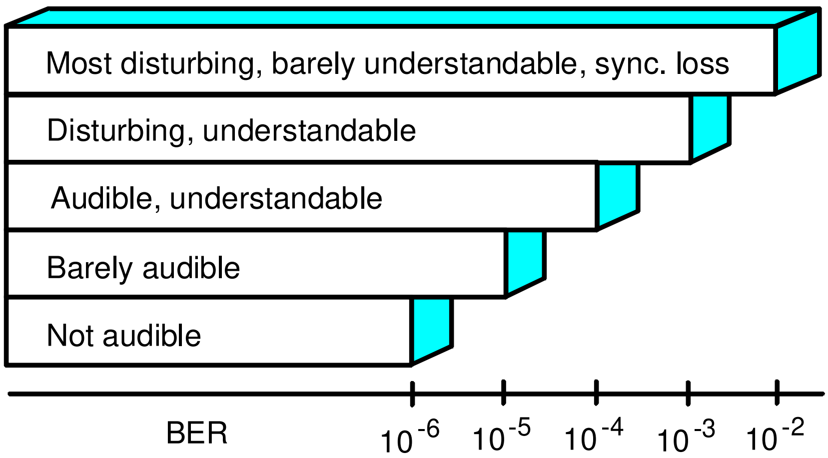
12.1.2 Noise factor

Other fundamental kinds of noise are the *shot noise* in pn-junction diodes, *partition noise* in transistors and *flicker noise*. In amplifiers the available *S/N* power ratio is degraded due to these additional noise sources within the amplifier. The noise factor of an amplifier (or any network) may be defined in terms of the signal-to-noise ratio as follows [41]:

107) $$F = \frac{\text{available } S/N \text{ power ratio at input}}{\text{available } S/N \text{ power ratio at output}}$$

12.1.3 Noise in digital systems

Figure 56 shows the bit-error-ratio (BER) as a function of receiver input level. The receiver threshold level is a function of the thermal noise (a function of the receiver bandwidth) and the noise factor of the receiver front end. Any additional noise will increase the BER and consequently reduce the system performance.



For traditional telephony the system may survive with a BER close to 10^{-3}, and as indicated above, a BER=10^{-6} represents no audible degradation. Systems carrying data traffic and in particular multi-media applications including live video normally require a very low BER for high quality transmission. A background BER below 10^{-12} is normally required, and the limit for operation is about BER = 10^{-6}. This results in more stringent requirements for noise limits in digital systems compared to former demands, and has an impact on acceptable interference levels.

To operate correctly, a digital system usually requires a signal-to-interference ratio *S/I* of 15 - 25 dB, according to the modulation scheme. This ratio may be found using

108) $$S/N_{(dB)} = L_{Te} - 10\log(kTB) - F_{(dB)}$$

where

L_{Te} - Receiver threshold level for a given BER (no interference) [dBW]
k - Boltzmann's constant
T - the absolute temperature in Kelvin
B - the IF bandwidth in Hertz
F - the receiver noise figure in decibel

Equation 108) gives the theoretical ratio. For practical systems an implementation margin (~ 1 dB) should be added to this number, giving a practical (*S/N*) ratio C_R. The C_R-values for Nera radios can be derived as given in table 9. Adding a 1 dB implementation margin results in the right-most column.

Radio type	Threshold $(\text{BER } 10^{-3})$	Noise figure	IF bandwidth	S/N theoretical	C_R practical
4x2 Mb/s	-87.0 dBm	5.0 dB	6 MHz	14 dB	15 dB
34 Mb/s	-82.5 dBm	4.5 dB	26 MHz	13 dB	14 dB
140 Mb/s	-73.0 dBm	4.1 dB	27 MHz	23 dB	24 dB
155 Mb/s	-73.0 dBm	4.5 dB	27 MHz	22 dB	23 dB

Table 9 Typical C_R-values for Nera equipment

The values in table 9 may vary slightly for the different frequency bands, mainly due to variations in noise figures. The numbers will of course be totally different if other modulation schemes are deployed. The modulation method both affects the required S/N-ratio and the IF bandwidth of the receiver.

12.2 Interfering signal's impact on receiver threshold levels

Only digital radio relay systems will be considered here. In analogue systems (FDM/FM systems), the noise contribution from interfering signals is added on a power basis to the thermal receiver noise, giving a deterioration of the system-value curve.

In digital systems (TDM systems), the presence of interfering signals increases the *receiver's threshold level* for a given bit-error ratio (BER). When an interfering signal is present, the S/I ratio is decreased, giving a receiver *threshold degradation.* To maintain the system performance (for an unchanged fading margin) the receiver input level during fading free time must be increased. Maintaining the receiver input unchanged would degrade the BER performance.

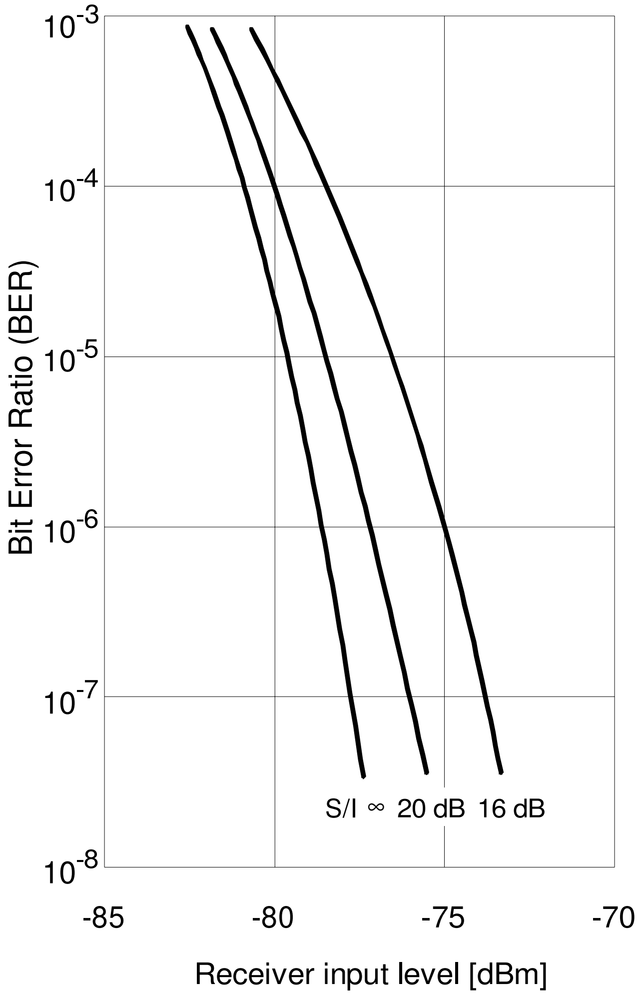


Figure 56 Typical BER-curves
34 Mb/s radio

During fading free time the S/I ratio is far better than the critical limit. The influence of the interfering signal is thus not detectable most of the time. The influence of interfering signal is first noticeable during fading conditions as a deterioration of the receiver threshold level. This is the same as a decrease of the path's fading margin. The conditions are that the interfering signal's field strength remains unchanged (non-faded) while the wanted signal fades. It is therefore of interest to discuss the correlation between fading of the wanted and the interfering signals. The signals are generally non-correlated when the wanted signal and the interference follow different paths.

12.2.1 Co-channel interference

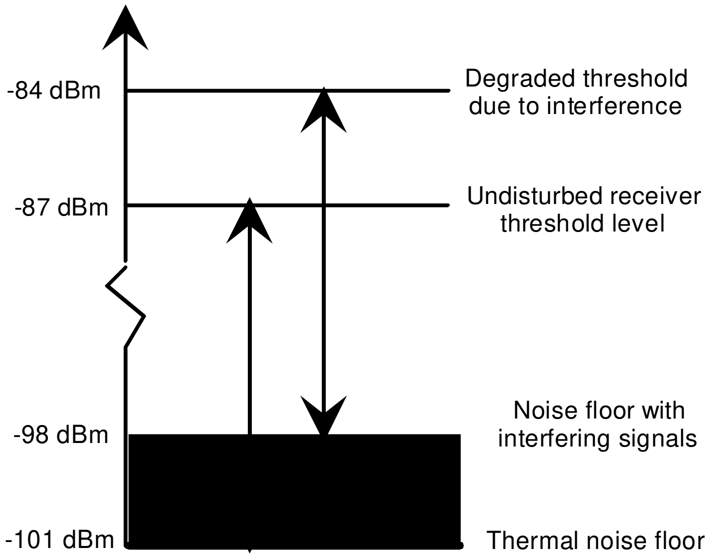


Figure 57 Threshold degradation

Presence of interfering signals will move the BER-curve in figure 56 to the right, giving a receiver threshold degradation. Let us consider a given receiver with 6 MHz bandwidth and a noise figure of 5 dB. The resulting thermal noise floor is -101 dBm. This receiver requires a 14 dB S/I ratio for a given BER, giving a threshold level of -87 dBm. An additional interfering signal with an input level of -101 dBm gives a total noise level of -98 dBm (3 dB increase). The resulting degraded threshold level is -84 dBm (3 dB degradation) as indicated in figure 57.

The degraded receiver threshold level L_{TeI} for a given interference level L_I may be calculated using the formula:

109) $$L_{TeI} = L_{Te} + 10\log\left(1 + 10^{((-L_{Te} + C_R + L_I)/10)}\right) \quad \text{[dBm]}$$

This gives a typical interference curve as shown in figures 58 and 60.

An interference level of -101 dBm corresponds to a threshold level of -84 dBm in figure 58 (compare with figure 57). The threshold degradation in figure 60 is found by finding the S/I ratio with the degraded threshold level (17 dB) using a few graphical iterations.

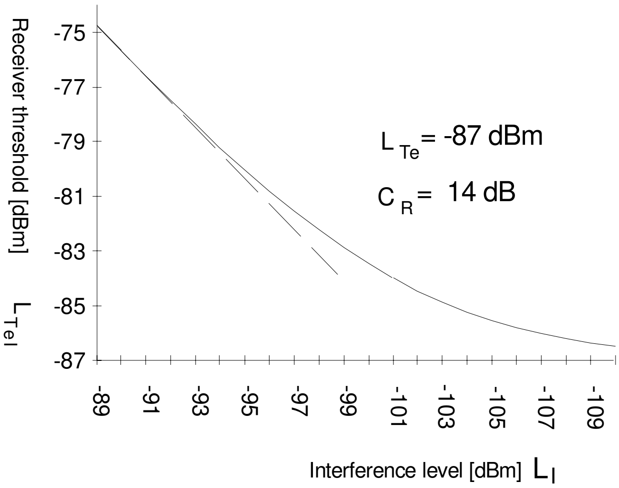


Figure 58 Interference curve (type 1)

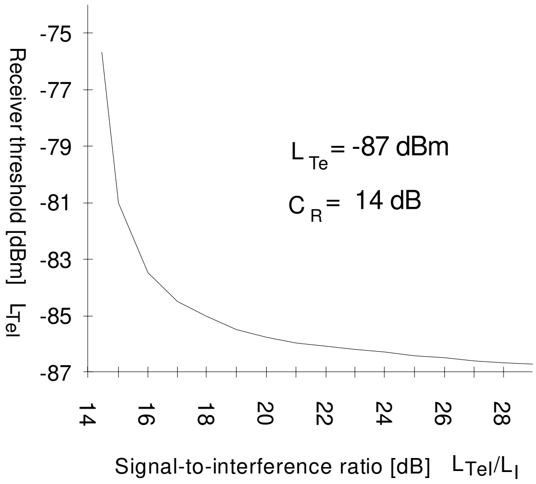


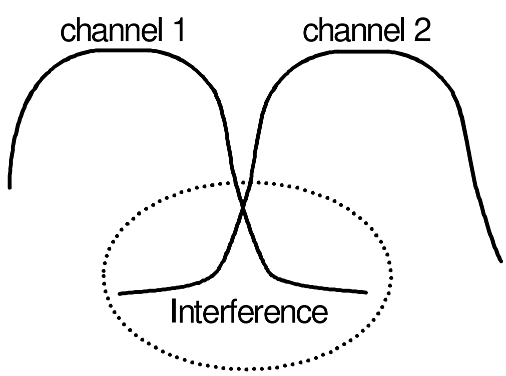
Figure 59 Interference curve (type 2)

The graph in figure 58 has got two asymptotes; one horizontal being the threshold level for the undisturbed receiver (no interference) L_{Te} (the x-axis). The other is the dashed line in figure 58, giving a dB by dB threshold degradation as a function of interference level.

The same two asymptotes for the graph in figure 60 are: One horizontal being the threshold level for the undisturbed receiver (no interference). The other is the vertical line (close to the y-axis) for a *S/N* ratio where the given BER no longer can be achieved. This asymptotic value corresponds to the C_R-value. If the *S/N* ratio gets poorer the required conditions to achieve the given BER is no longer maintained, and the BER is increased.

12.2.2 Adjacent channel interference

The channel filter will suppress any signal outside the receiver bandwidth of the radio. The channel filter attenuation for a specific frequency offset should thus be subtracted from the values given in table 9 to give the required C_R-values for adjacent channel interference. The adjacent channel separation for the given frequency plan will determine the channel filter attenuation. Table 10 gives some typical values for a few examples based on the C_R-values from table 9. In computerised interference calculations, C_R-values in table 9 may be combined with



channel filter attenuation for interfering signals with various frequency offsets in complex systems to calculate degraded threshold levels with several interfering signals.

The C_R-values for Nera equipment for a few various frequency plans are given in table 10.

Radio type	Frequency band	Frequency separation	Filter attenuation	C_R practical
4x2 Mb/s	15 GHz	7 MHz	25 dB	-10 dB
34 Mb/s	7 GHz	14 MHz	30 dB	-16 dB
140 Mb/s	6 GHz	40 MHz	36 dB	-12 dB
155 Mb/s	6 GHz	29.65 MHz	26 dB	-3 dB

Table 10 Examples of C_R-values for adjacent channel interference.

In complex radio relay systems with several receivers operating in the same frequency band at the same station, interference calculations should be performed to verify acceptable interference levels. Possible receiver threshold degradation may be found using formula 109) and C_R-values similar to those given in tables 9 and 10. In computerised interference calculations, C_R-values are more convenient to use than the interference curves shown in figures 58 and 60. These values make automatic checking of threshold degradations possible for very complex systems, involving both co-channel and adjacent channel interference.

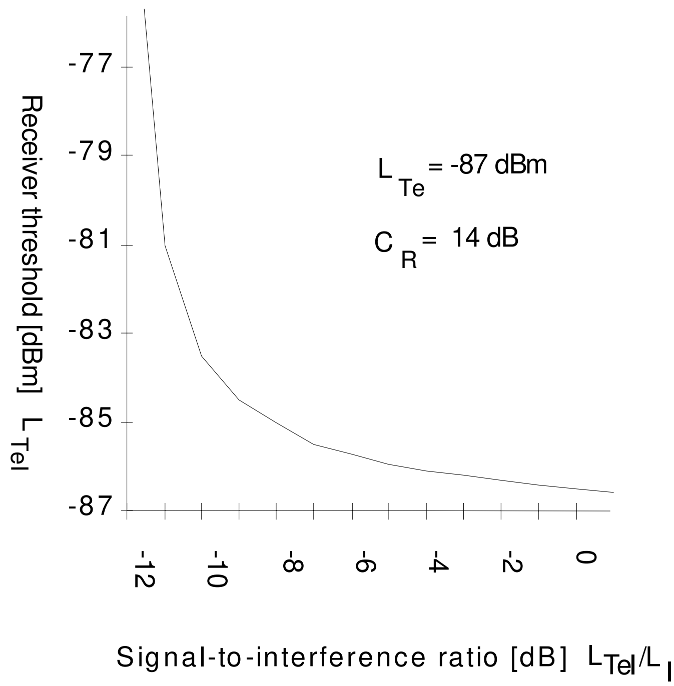


Figure 60 Adjacent channel interference curve (type 2)

Chapter

13

Propagation in interference calculations

Before interference calculations are performed, the relevant disturbing radio relay stations should be selected from a numerous collection of stations in the area of interest. This chapter introduces techniques for systematic selection based on statistical assumptions [50].

13.1 Co-ordination area

The co-ordination area between radio relay stations is defined as the area around a given station where a possible interfering station may be situated. Stations outside this area will not affect the given station.

Since microwave antennas are highly directive, a keyhole concept is used in co-ordination distance analysis.

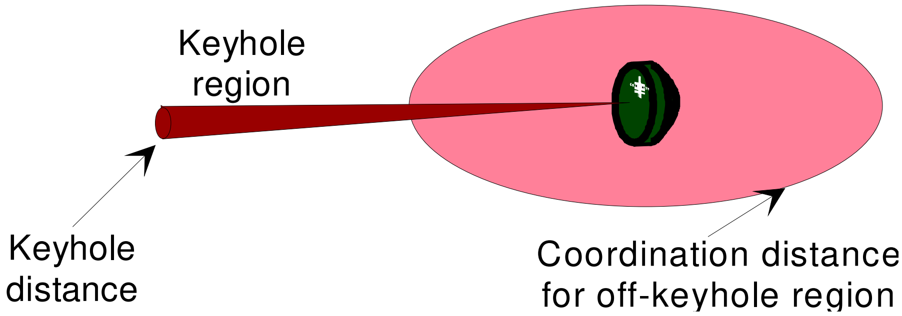


Figure 61 Keyhole concept

The co-ordination distance is found using

110) $L_I = P_{Tx} + [G_{Tx} - D_{Tx}(\theta')] + [G_{Rx} - D_{Rx}(\theta)] - L(d)$

where

$L_I =$	Received interference level [dBm]
$P_{Tx} =$	Transmitted power from disturbing station [dBm]
$G_{Tx/Rx} =$	Antenna gain transmitter/receiver [dB]
$D_{Tx/Rx} =$	Antenna discrimination transmitter/receiver [dB]
$L(d) =$	Path loss [dB]
θ and θ	are defined in figure 62.

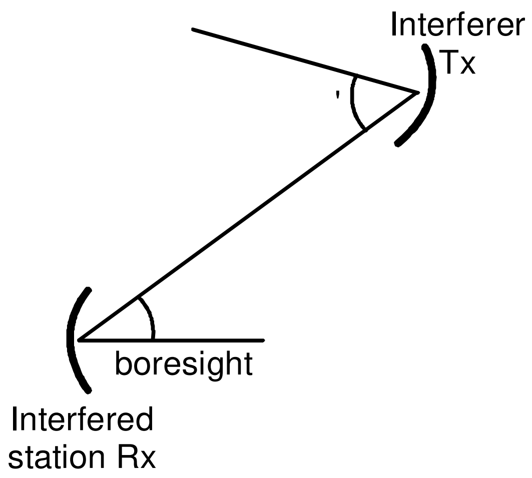


Figure 62 Simplified radio relay network

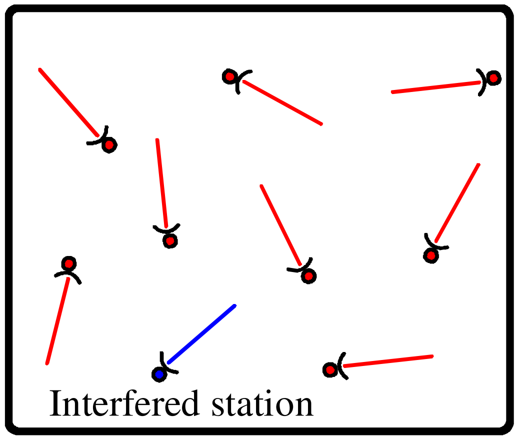


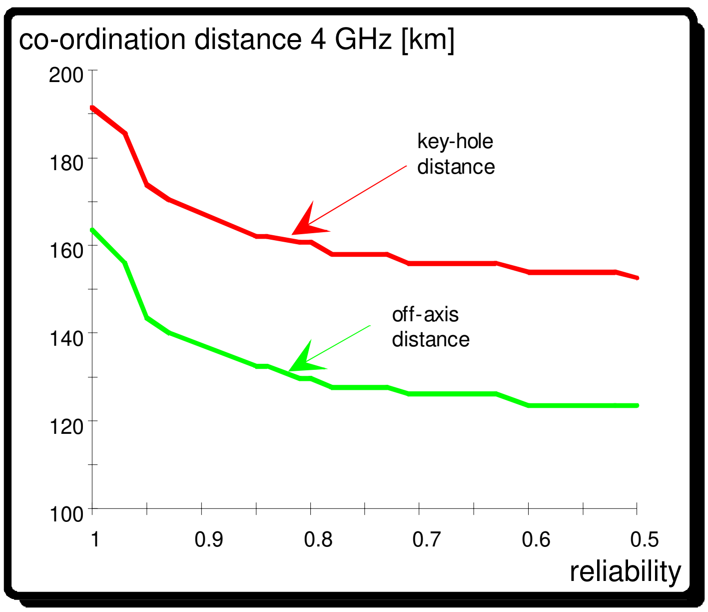
Figure 63 Station distribution

Assume that a signal to interference ratio $S - I \geq X$ dB is required for your system to operate correctly. The required signal level is then given by

111) $S \geq P_{Tx} + [G_{Tx} + D_{Tx}(\theta')] + [G_{Rx} - D_{Rx}(\theta)] - L(d) + X$

The required signal level may be calculated for different values of θ and θ'. For $D_T(\theta') = 0$ (worst case) all interfering stations are assumed to point directly towards the interfered station. The co-ordination distance calculated under this condition will specify a region within which all interfering stations will be located $(\max P_T$ and $G_T)$ must be guestimated.

The worst case assumption $(D_T(\theta') = 0)$ may give a large co-ordination area including a large number of stations. Instead consider homogenous distributed and randomly oriented possibly interfering stations as indicated in figure 63. Calculate the co-ordination area for angles $\theta = \theta_1$ or larger.



The reliability of this co-ordination area will be:

112) $R(\theta'_1) = 1 - \frac{\theta'_1}{180}$

13.2 Propagation mechanisms

13.2.1 Long-term interference mechanisms

The long-term interference mechanisms are

- diffraction
- troposcatter
- line-of-sight

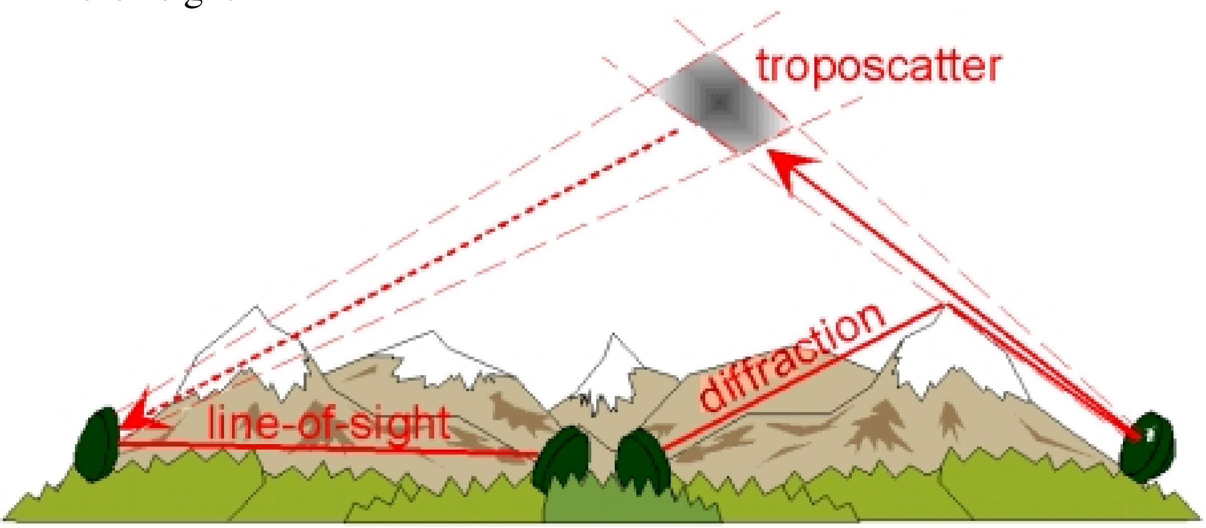


Figure 64 Long-term interference mechanisms

13.2.2 Short-term interference mechanisms

The short-term interference mechanisms are

- layer refraction/reflection
- hydrometer scatter
- enhanced line-of-sight

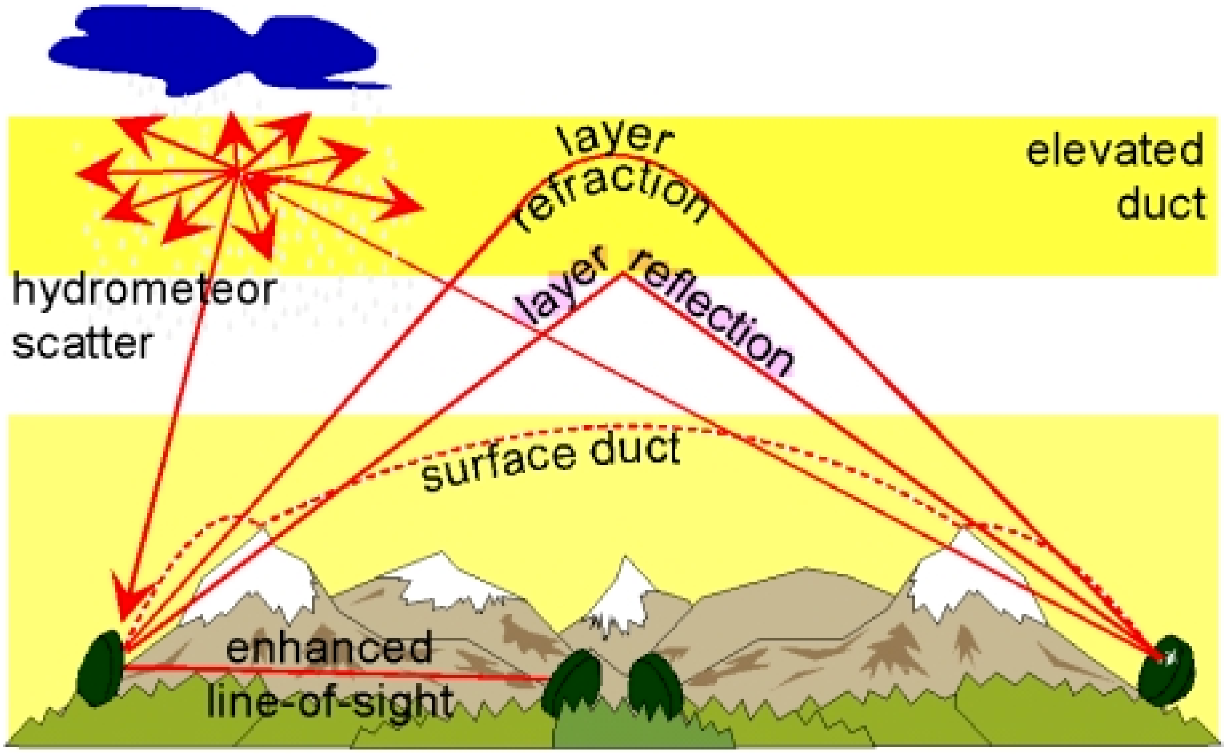


Figure 65 Short-term interference mechanisms.

13.3 Prediction methods

There are one global and one European prediction model. The European method offers improved precision for north-west Europe. The two methods are essentially the same apart from the method of defining the radio-meteorological influences affecting the anomalous propagation conditions on the path.

13.3.1 Global procedure

Outline:

1. Decide whether an average year or worst-month prediction is required.

2. Assemble the basic input data.

3. Derive the annual or worst-month radio-meteorological data from the maps provided (figure C1 through C4).

4. Analyse the path profile, and classify the path according to the path geometry.

5. Identify which individual propagation models need to be invoked.

6. Calculate the individual propagation predictions using each of the models identified in step 5.

7. Combine the individual predictions to give the overall statistics.

Let us go through the procedure outline step by step:

STEP 1:

The choice of average year or worst-month prediction is dictated by the quality (i.e. the performance and availability) objectives of the interfered-with radio system.

STEP 2:

The input data applicable to the calculation procedure is found in table 11.

Parameter	Preferred resolution	Description
f	0.01 GHz	Frequency [GHz]
p	0.001%	Required time percentage(s) for which the calculated basic transmission loss is not exceeded
φ_t, φ_r	0.001°	Latitude of station
ψ_t, ψ_r	0.001°	Longitude of station
h_{tg}, h_{rg}	1 m	Antenna centre height above ground level [m]
G_t, G_r	0.1 dBi	Antenna gain in the direction of the horizon along the great-circle interference path [dBi]

Table 11 Input data

STEP 3:

The purpose is to find the diffraction loss for 50% (or less) of the time. The median effective earth radius factor k_{50} is found by:

113) $k_{50} = \dfrac{157}{157 - \Delta N}$

where ΔN is found from figures D1 and D2 in appendix D [50].

The corresponding effective earth radius is then

114) $a_e = 6\,375 \cdot k_{50}\ [\mathrm{km}]$

The effective earth radius and radius factor for other percentages of time may be found using:

115) $k(p) = k_{50} + (5 - k_{50}) \dfrac{1.7 - \log(p)}{1.7 - \log(\beta_0)} \qquad p\% < 50\%$

where β_0 is found using figures D3 and D4 in appendix D [50].

116) $a(p) = 6375 \cdot k(p)\ [\mathrm{km}]$

STEP 4:

13.3.2 Path classification

1. Test for transhorizon

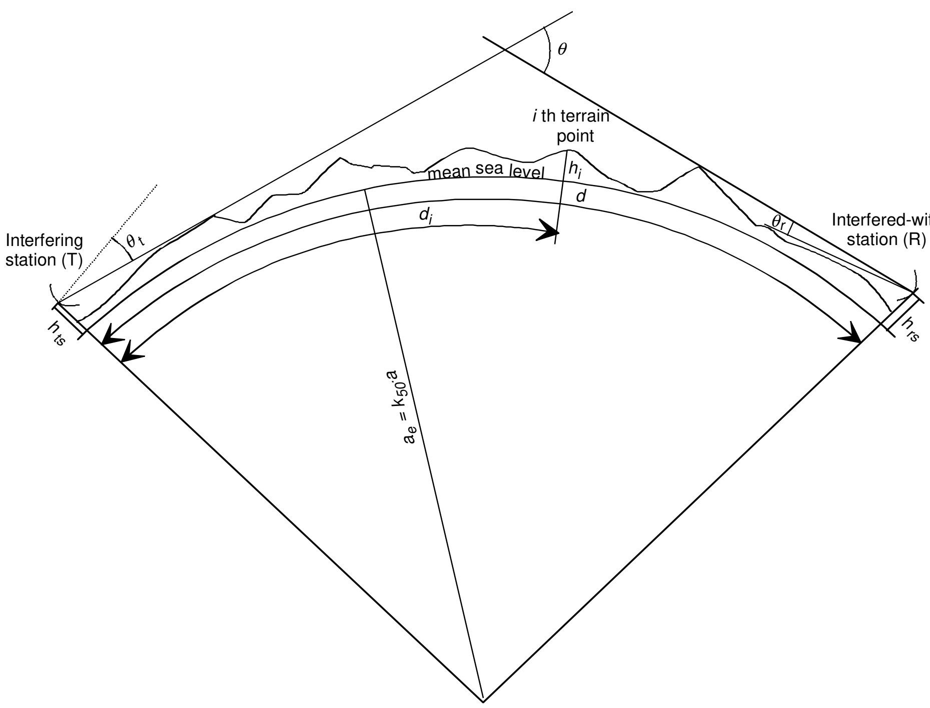


Figure 66 Model for path classification

The path is transhorizon if $\theta_{\max} > \theta_{td}$

where

117) $\theta_{\max} = \max_{i=1}^{n-1}[\theta_i]$

118) $\theta_i = \frac{h_i - h_{ts}}{d_i} - \frac{10^3 \cdot d_i}{2 \cdot a_e}$ [mrad]

119) $\theta_{td} = \frac{h_{rs} - h_{ts}}{d} - \frac{10^3 \cdot d}{2 \cdot a_e}$ [mrad]

2. Test for sub-path diffraction

The path has sub-path diffraction if $\theta_{f_{\max}} > \theta_{td}$

where

120) $\theta_{f_{\max}} = \max_{i=1}^{n-1}[\theta_{f_i}]$

121) $\theta_{f_i} = \frac{(h_i + R_i) - h_{ts}}{d_i} - \frac{10^3 \cdot d_i}{2 \cdot a_e}$ [mrad]

122) $R_i = 17.392\sqrt{\frac{d_i(d - d_i)}{d \cdot f}}$ [m]

STEP 5:

Analyse of the path profile for $p = 50\%$ is done using table 12.

Classification	Models required (with conditions)
Line-of-sight with first Fresnel zone clearance	Line-of-sight
Line-of-sight with sub-path diffraction (1)	Line-of-sight; diffraction
Trans-horizon	Diffraction $(d \leq 200\ \text{km and } \beta_0 < 50\%)$ Troposcatter $(\theta \geq 8\ \text{mrad})$ Ducting/layer reflection $(d > 20\ \text{km})$

(1) Sub-path diffraction is defined by a terrain incursion into the first Fresnel zone.

Table 12 Path analysis

13.3.3 Ducting interference

The transmission loss between two terminals immersed within a duct is given by

123) $L_b = 92.45 + 20\log f + 10\log d + C_1 d + L_c$

where

C_1 is a constant

L_c is a coupling loss given by

$$L_c = 10\log\left(\frac{\Delta\theta}{\theta_B}\right) \quad \text{for } \Delta\theta < \theta_B$$

$$L_c = 0 \quad \text{for } \Delta\theta \geq \theta_B$$

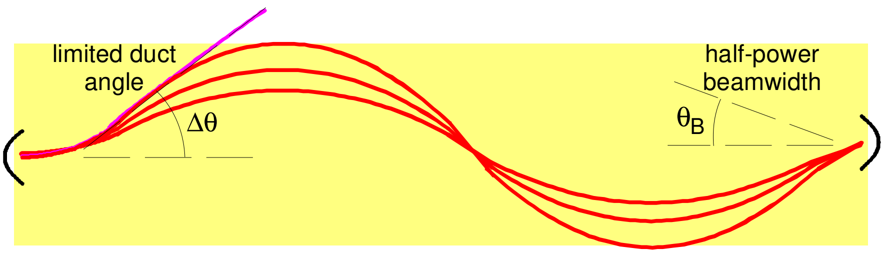


Figure 67 Rays in radio duct.

Chapter 14

Frequency planning

This chapter will cover the principles of frequency planning without going into detailed interference calculations and countermeasures to interference problems. This will be covered separately in chapter 15.

14.1 Setting up the frequency plan

Certain basic rules should be followed setting up the frequency plan. This is necessary in order to utilise the available frequency range in the most economical way, and for making the planning work more efficient. All frequencies used in a radio-relay network should normally be selected from an established frequency plan, established either by an international or national organisation.

14.1.1 Conditions

Radio signals have to be frequency-separated if neither antenna discrimination nor topographical shielding provides the necessary suppression of interfering signals. The degree of separation depends on the transmitted bandwidth - the *spectrum bandwidth*. This separation - called *adjacent-channel separation* - should be as small as possible to give a frequency economic solution. This requires some kind of standardisation, a *frequency plan*.

The system uses two different frequencies, one for the *go* and one for the *return* direction. Their separation - called *transmitter (Tx) to receiver (Rx)* or *duplex* separation - depends on the filters in the receiver that have to suppress their own transmitter's frequency (in the order of 140 dB suppression!). The larger duplex separation, the easier it is to realise the filters. The duplex separation is specified in the frequency plan.

The next problem is *inter-modulation products*. When more than one radio frequency is present, inter modulation products will appear due to non-linearities in the equipment. It must be avoided that these or other inter modulation products disturb a third receiver. A pre-established frequency plan considering this aspect is a requisite for a rational frequency allocation.

As we know, interfering radio signals do not stop at a country's border. This motivates international agreements and co-operations, established world-wide by the International Telecommunications Union (ITU).

14.1.2 International frequency plans

The total radio spectrum available is allocated to the various services (radio astronomy, radar, mobile communications, etc.) by the ITU's World Administrative Radio Conference (*WARC*). In the *Radio Regulations* [35], the frequency bands apportioned to the fixed services are listed. Within the ITU, Radiocommunication Bureau (*ITU-R*) is responsible for providing RF-channel arrangements, i.e. frequency plans. These plans are published as *recommendations* or *reports*. [50]

There are basically three ways of utilising these frequency plans, depending on the type of equipment, interference considerations and need for spectrum efficiency.

14.1.2.1 Alternated channel arrangement

The most widely used utilisation is the alternated channel arrangement as indicated in Figure 69. In this case every second channel is utilised using the same polarization, whereas adjacent channels operate on opposite polarizations.

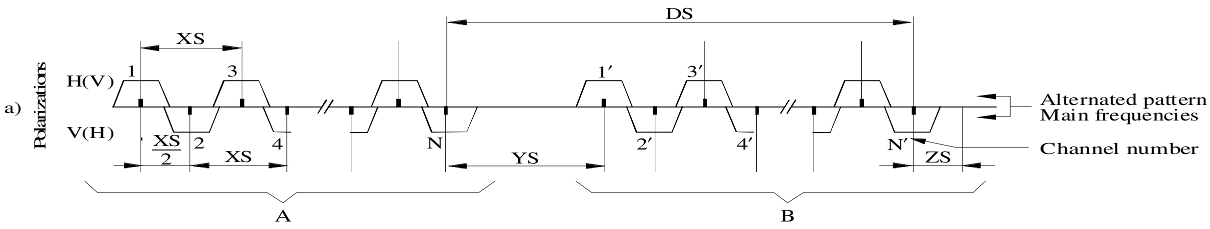


Figure 68 Alternated channel arrangement

This arrangement can be used (neglecting the co-polar adjacent channel interference contribution) if the following holds:

124) $$XPD_{\min} + (NFD - 3) \geq (C/I)_{\min}$$

where

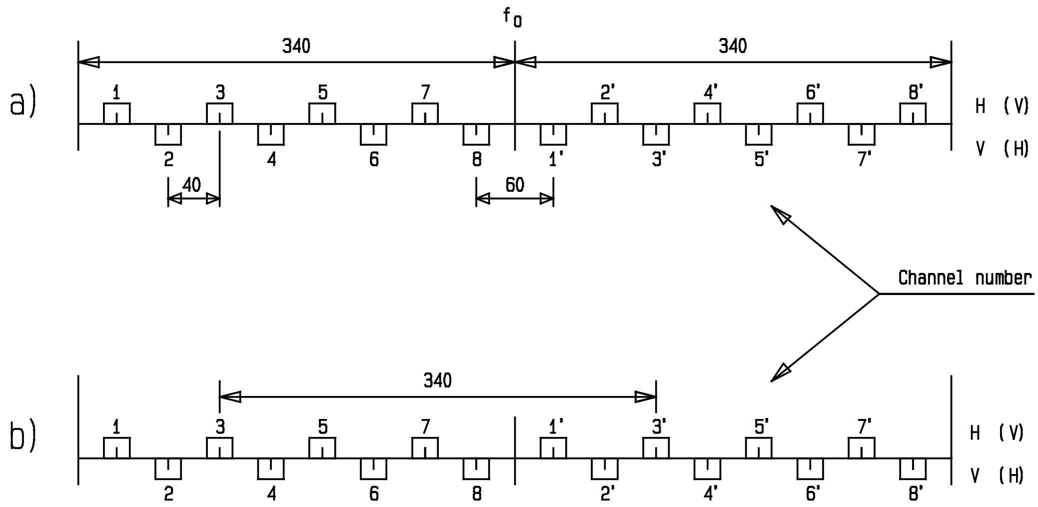
XPD$_{min}$ is the minimum cross polar discrimination as defined in chapter 11 Cross-polar interference.

NFD is the net filter discrimination defined as

125) $$NFD = \frac{\text{Adjacent channel received power}}{\text{Adjacent channel power received after RF, IF and BB filters}}$$

(C/I)$_{\min}$ is the minimum carrier (or signal) to interference ratio for a given BER limit (typically 10^{-3} or 10^{-6}). The requirements in equation 125) is normally easily fulfilled by standard performance antennas and radio equipment, but the spectrum efficiency is limited with use of single polarised antennas as only every second channel can be used on the same path as indicated in equation 125).

An example for an ITU-R-recommended frequency plan is the one for the upper 6 GHz band, Recommendation 384 [48]. This recommendation consists of one frequency plan for systems with up to 2700 telephone channels (140 Mb/s or synchronous digital hierarchy bit rates) using up to 8 go and 8 return radio channels. Another frequency plan is obtained by interleaving additional channels for systems with up to 1260 telephone channels using up to 16 go and 16 return channels.



a) Channel arrangement for antennas with double polarization
b) Channel arrangement for antennas with single polarization
or common TX/Rx antenna with double polarization.

(All frequencies are in MHz)

Figure 69 ITU-R rec. 384 [48] (the upper 6 GHz band).

Figure 69 shows the main frequency plan for the 2 times 8 channels arrangement. The frequency band is divided into two half bands, one half band for the go or transmitter (Tx) frequencies, the other one for the return or receiver (Rx) frequencies. The half bands have space for 8 paired radio channels. To each of the channels in the lower half band corresponds one with the same channel number in the upper half band. The *duplex* separation is the same for all channels (340 MHz). The channel spacing Γ is 40 MHz. The exact channel centre frequencies can be calculated from the formulas

126 a) *lower half of the band*: $f_n = f_0 - 350 + 40n$

b) *upper half of the band*: $f'_n = f_0 - 10 + 40n$

$$\text{where} \quad n = 1,..,8$$
$$f_0 = 6770$$

The frequency unit is MHz

Adjacent channels can be operated simultaneously with the radio waves on orthogonal polarizations. The degree of discrimination between the polarizations depends on the azimuth angle and the antenna type used.

14.1.2.2 Co-channel arrangement

Where frequency congestion is a problem, co-channel operation may be a solution. In this arrangement every radio-channel is utilised twice for independent traffic on opposite polarizations for the same path.

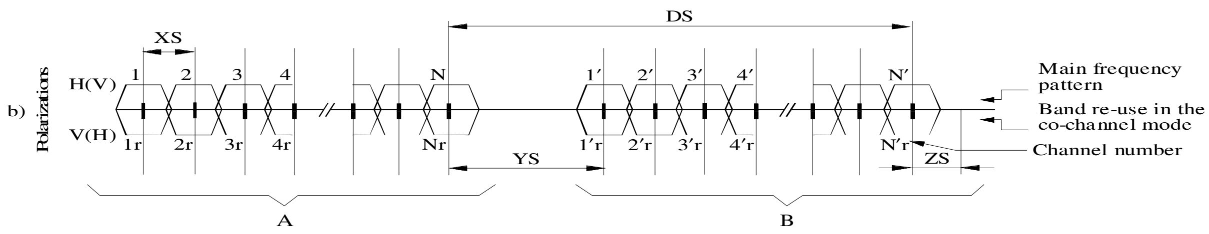


Figure 70 Co-channel arrangement

This arrangement puts more stringent demands on the antenna and radio performance, as the following demand must be fulfilled.

127) $$10\log \frac{1}{\dfrac{1}{10^{\frac{XPD+XIF}{10}}}+\dfrac{1}{10^{\frac{NFD_a-3}{10}}}} \geq (C/I)_{\min}$$

where

NFD_a is the net filter discrimination evaluated at XS frequency spacing

XIF is the XPD improvement factor for the XPIC device (if implemented)

14.1.2.3 Interleaved arrangement

The interleaved mode is kind of a compromise of the alternated mode and the co-channel mode. This mode is typically applicable to low capacity systems where the bandwidth of the signal may be less than the channel separation. In this case the centre frequency of the radio channel on the opposite polarization is half-way between the adjacent channels.

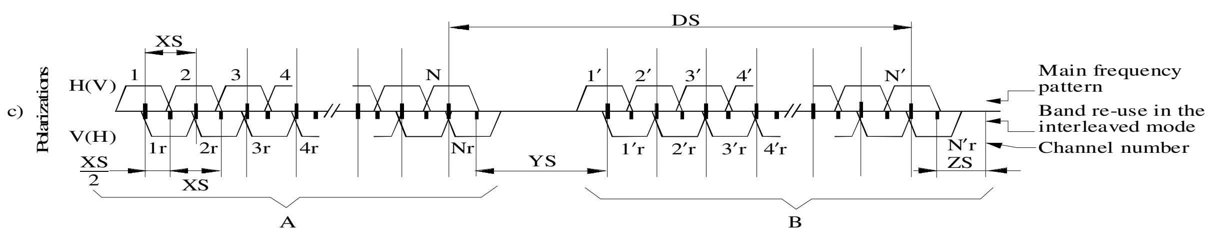


Figure 71 Interleaved arrangement

This interleaved channel arrangement can be used if:

$$10\log\frac{1}{\dfrac{1}{10^{\frac{XPD+(NFD_b-3)}{10}}}+\dfrac{1}{10^{\frac{NFD_a-3}{10}}}}\geq(C/I)_{\min} \tag{128}$$

where

NFD_b is the net filter discrimination evaluated at XS/2 frequency spacing.

The other parameters have their previous signification.

Table 13 is a summary of the frequency plans recommended by ITU-R [50].

Band [GHz]	Frequency range [GHz]	Channel spacing [MHz]	ITU-R rec.
1.4	1.35 - 1.53	0.25; 0.5; 1; 2; 3.5	1242
2	1.427 - 2.69 1.7 - 2.1; 1.9 - 2.3 1.7 - 2.3 1.9 - 2.3 1.9 - 2.3 1.9 - 2.3 2.3 - 2.5 2.29 - 2.67 2.5 - 2.7	0.5 (pattern) 29 14 3.5; 2.5 (patterns) 14 10 1; 2; 4; 14; 28 0.25; 0.5; 1; 1.75; 2; 3.5; 7; 14; 2.5 (patterns) 14	701 382 283 1098 1098, Annexes 1,2 1098, Annex 3 746, Annex 1 1243 283
4	3.8 - 4.2 3.6 - 4.2 3.6 - 4.2	29 10 (pattern) 90; 80; 60; 40	382 635 635, Annex 1
5	4.4 - 5.0 4.4 - 5.0 4.4 - 5.0 4.54 - 4.9	28 10 (pattern) 40; 60; 80 40;20	746, Annex 2 1099 1099, Annex 1 1099, Annex 2
Lower 6	5.925 - 6.425 5.85 - 6.425	29.65 90; 80; 60	383 383, Annex 1
Upper 6	6.425 - 7.11 6.425 - 7.11	40; 20 80	384 384, Annex 1

continued…

Band [GHz]	Frequency range [GHz]	Channel spacing [MHz]	ITU-R rec.
7	7.425 - 7.725 7.425 - 7.725 7.435 - 7.75 7.11 - 7.75	7 28 5 28	385 385, Annex 1 385, Annex 2 385, Annex 3
8	8.2 - 8.5 7.725 - 8.275 7.725 - 8.275 8.275 - 8.5	11.662 29.65 40.74 14; 7	386 386, Annex 1 386, Annex 2 386, Annex 3
10	10.3 - 10.68 10.5 - 10.68 10.55 - 10.68	20; 5; 2 7; 3.5 (patterns) 5; 2.5; 1.25 (patterns)	746, Annex 3 746, Annex 1 746, Annex 2
11	10.7 - 11.7 10.7 - 11.7 10.7 - 11.7 10.7 - 11.7	40 67 60 80	387, Annexes 1 and 2 387, Annex 3 387, Annex 4 387, Annex 5
12	11.7 - 12.5 12.2 - 12.7	19.18 20 (pattern)	746, Annex 4, § 3 746, Annex 4, § 2
13	12.75 - 13.25 12.75 - 13.25 12.7 - 13.25	28; 7; 3.5 35 25; 12.5	497 497, Annex 1 746, Annex 4, § 1
14	14.25 - 14.5 14.25 - 14.5	28; 14; 7; 3.5 20	746, Annex 5 746, Annex 6
15	14.4 - 15.35 14.5 - 15.35 14.5 - 15.35	28; 14; 7; 2.5 2.5 (pattern) 2.5	636 636, Annex 1 636, Annex 2
18	17.7 - 19.7 17.7 - 21.2 17.7 - 19.7 17.7 - 19.7 17.7 - 19.7	220; 110; 55; 27.5 160 220; 80; 40; 20; 10; 6 3.5 13.75; 27.5	595 595, Annex 1 595, Annex 2 595, Annex 3 595, Annex 4
23	21.2 - 23.6 21.2 - 23.6 21.2 - 23.6 21.2 - 23.6 21.2 - 23.6 21.2 - 23.6 22.0 - 23.6	3.5; 2.5 (patterns) 112 to 3.5 28; 3.5 28; 14; 7; 3.5 50 112 to 3.5 112 to 3.5	637 637, Annex 1 637, Annex 2 637, Annex 3 637, Annex 4 637, Annex 5 637, Annex 1

continued…

Band [GHz]	Frequency range [GHz]	Channel spacing [MHz]	ITU-R rec.
27	24.25 - 25.25 24.25 - 25.25 25.25 - 27.7 25.25 - 27.7 27.5 - 29.5 27.5 - 29.5 27.5 - 29.5	3.5; 2.5 (patterns) 56; 28 3.5; 2.5 (patterns) 112 to 3.5 3.5; 2.5 (patterns) 112 to 3.5 112; 56; 28	748 748, Annex 3 748 748, Annex 1 748 748, Annex 2 748, Annex 3
31	31.0 - 31.3	50; 25	746, Annex 7
38	36.0 - 40.5 36.0 - 37.0 37.0 - 39.5 38.6 - 40.0 39.5 - 40.5	3.5; 2.5 (patterns) 112 to 3.5 140; 56; 28; 14; 7; 3.5 50 112 to 3.5	749 749, Annex 3 749, Annex 1 749, Annex 2 749, Annex 3
55	54.25 - 58.2 54.25 - 57.2 57.2 - 58.2	3.5; 2.5 (patterns) 140; 56; 28; 14 100	1100 1100; Annex 1 1100, Annex2

Table 13 ITU-R recommended frequency plans.

14.1.3 Adjacent-channel separation

For the rest of this chapter the alternated channel arrangement will be used to explain frequency allocations and utilisation of the frequency plans. For details on co-channel operation, please refer to chapter 11.

14.1.3.1 Common path

When operating more than one radio circuit on the same antenna (a n+1 frequency diversity configuration) the channels chosen must have a certain defined separation Δ. This separation coincides with the channel spacing Γ according to the frequency plan, but may also be a *multiple* of it. For the main part of the channel arrangements, these separations are stated in the ITU-R recommendation concerned. In the upper 6 GHz plan (rec. 384 [48]) the recommended adjacent channel separation Δ for operation on one common antenna is

129 a) for single polarised systems:
$\Delta_c = x \cdot 2\Gamma \;\; or \;\; \Delta_c = x \cdot 80\, MHz$

b) for dual polarised systems:
$\Delta_x = y \cdot \Gamma \;\; or \;\; \Delta_x = y \cdot 40\, MHz$

$(\Gamma = 40\, MHz,\ x = 1,2,3;\ y = 1,..,8)$

When applying co-polar operation, a single polarised antenna can be used. For cross polarization, a dual polarised antenna has to be chosen, together with either two waveguide runs, or a circular waveguide. To keep the costs down, co-polar polarization should be the first choice.

Since these adjacent-channel separations are chosen to avoid mutual interference between the channels concerned, interference between these channels can be excluded from the interference calculations.

13.1.3.2 Separate paths

Interference between RF channels on separate antennas or different paths is negligible if the frequency separation δ between the channels is so large that the disturbing channel's centre frequency falls within the stop-band of the wanted channel's filter. The exact characteristics of the channel filter have to be taken from the equipment specification.

Interference paths between RF channels on different paths (antennas) with a separation $\geq \delta$ (for the equipment concerned) can be excluded from the interference considerations.

14.2 Allocation of radio frequencies

14.2.1 Preparations

Draw a network diagram to scale and angle the geographical layout of your system. Include **all** known systems operating (existing and planned) within the frequency band concerned. (See figure 72.)

14.2.2 Conditions

Each frequency band is divided into two half bands, the lower **A**, and the upper **B**. For a radio path the transmitting (Tx) and receiving (Rx) frequencies will nearly always be paired: they will have the same channel number, with opposite **A/B** indices. Channels in the lower half band **A** are unmarked (ch. 3), and channels in the upper half band **B** are marked (ch. 3'). Only the Tx numbering is shown in the network chart.

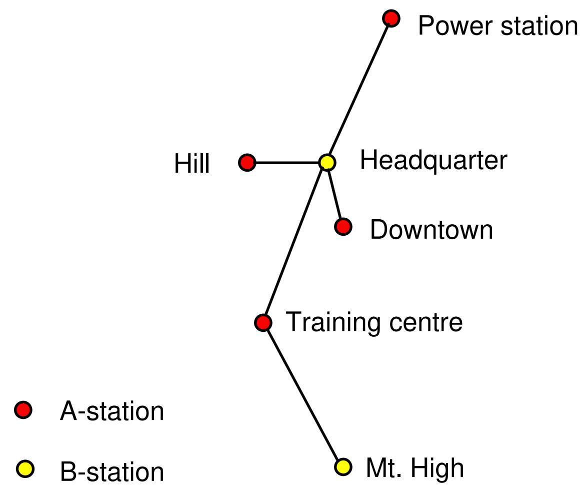


Figure 72 Radio-relay network

All transmitter frequencies in the same station have to be selected from the same half band. Stations with transmitters operating in the lower half band are called *A-stations*. The receiver on A-stations operates in the upper half band.

> *If the transmitter frequency (or half band) has been chosen for one transmitter at one station, the allocation of the half bands (A or B) for <u>all other</u> stations and transmitters in the network is determined.*

There is an important deviation from this rule. A passive repeater is both an **A** and a **B** station. Since no frequency conversion is effected, an incoming **A** frequency is re-emitted as an **A** frequency. The same is true for the **B** frequency in the other direction. The same arguments are also valid to a RF-repeater where no frequency conversion is performed. For the purpose of frequency allocation, passive- and RF-repeaters can be disregarded.

14.2.3 Frequency determination

14.2.3.1 General considerations

If your radio link plan already includes existing RL equipment, operating in the same frequency band, mark them as **A** or **B** stations in the network chart. In this case, the **A** and **B** designations for all other stations are determined.

If no equipment is present in the frequency band concerned, find out whether there might be another station, not included in the planned network, but close to one of the planned stations, with frequencies already allocated from that particular band. If this question is affirmative,

- and a future cross connection between the two networks can be implemented by one radio path only (or an odd number of hops):

  designate the half band with the opposite A/B label to the new station; thus determining the half bands for all the other stations.

- and a future cross connection has to be implemented by two (or an even number of hops):

  designate the half band with the same A/B label to the new station; thus determining the half bands for all the other stations.

If the answer is negative; start with any of the stations and allocate an arbitrary half band for it.

14.2.3.2 Backbone network

Frequency allocation for radio relay networks can be done in several ways, depending on the network complexity, future plans, etc. The frequency planning procedure also depends on how detailed the available information is. To illustrate this, two different DRL-networks are used; the one in figure 72 for the detailed planning, and the one in figure 73 for the straight forward solution.

To illustrate this method the network in figure 73 is used.

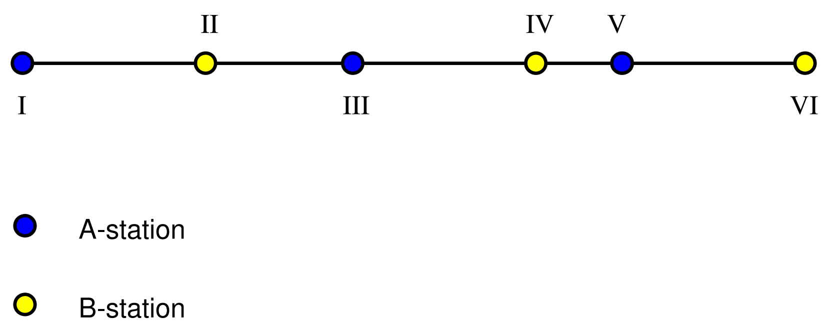


Figure 73 Simplified DRL-network.

Start in the same way as in the detailed method by selecting a frequency in the lower edge of the band for station I. Selecting channel 1 for the regular channel, gives the Tx- and Rx-frequencies listed in table 14.

	Ch. #	Station I (A)	Station II (B)
Tx1	1	6460 MHz / V	6800 MHz / V
Tx2	3	6540 MHz / V	6880 MHz / V
Rx1	1	6800 MHz / V	6460 MHz / V
Rx2	3	6880 MHz / V	6540 MHz / V

Table 14 Tx- and Rx- frequencies / A- and B- stations.

Trying to economise the use of RF-channels by using HP antennas all over, the following procedure should be used:

> **Change polarization and channel numbers on every second path throughout the system.**

Following this procedure for the system in figure 73, gives the frequency allocation shown in figure 74. Changing channels and polarization like this, prevent interference problems due to over-shoot in the system. The transmitter at station I could interfere with the receiver at station IV, but using different polarizations, give approximately 30 dB additional attenuation. This attenuation is sufficient to prevent adjacent-channel interference in the system.

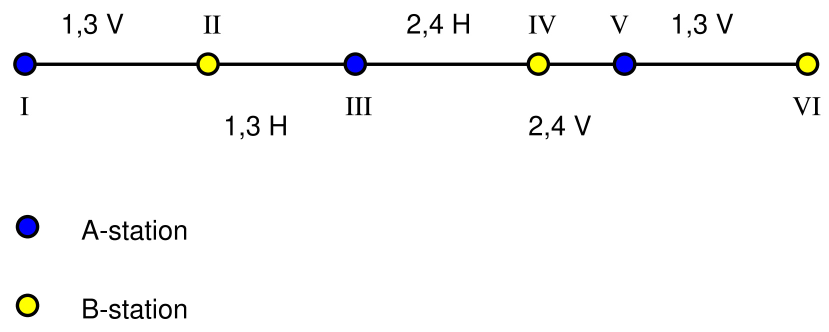


Figure 74 Frequency allocation for simplified DRL-network.

13.2.3.2.1 Repeated use of the same radio frequency

The same radio frequency should be used whenever possible to economise with the radio frequencies available. For digital radio links, the level of the interfering signal L_I, should be x dB below the receiver threshold level L_{Te}, where x corresponds to the S/I ratio for the threshold level concerned (see next chapter).

In nodal points this normally requires antenna discriminations in the order of $(S/I + F)$ where F is the fading margin for the path of interest.

14.2.3.2.2 Detailed planning

The network in figure 72 is used to illustrate the detailed planning procedure. A 140 Mb/s DRL system is to be implemented following the ITU-R rec. 384-5 [48] frequency plan. This gives the following technical data:

$$\Gamma = 40\ MHz$$

$$\Delta_c = 2 \cdot \Gamma = 80\ MHz$$

$$\Delta_x = \delta_{c/x} = 40\ MHz$$

Start with the nodal point having the largest quantities of transmitters. This is "Headquarters" in figure 72. This station has been decided to operate in the upper half band (B-station).

The system is assumed to work in a 1+1 configuration. This gives two RF channels in each half band, allowing both channels to operate in the same polarization. If the channel separation is $\geq \Delta$, they can also be transmitted from the same antenna.

Start by selecting a frequency (preferably at the lower edge of the half band). *Note that existing equipment may restrict this choice*. The radio channel for the second channel in this 1+1 system is then selected according to the rules for *adjacent-channel separation using a common antenna*. To keep the system cost down, parallel polarization should be tried as the first choice.

In order to economise frequencies, the first approach should be to apply the same frequencies for all of the system. Possible interferences call for more expensive antennas or use of different frequencies. Individual projects give you different decisions choosing one of these countermeasures. If new frequencies are chosen, the rules for *adjacent-channel separation for different antennas* should be used.

<u>Example 1</u>

Start with the path Power station - Headquarters.

⊗ Select channel **1**, vertical polarization for the first channel.

⊗ This gives channel **3** for the second channel, on common antenna and same polarization.

$$\Delta_c = 2 \cdot \Gamma$$

The corresponding frequencies / polarizations for the first choice frequency plan is given in table 14.

These frequencies would apply to all A- and B-stations as a first choice giving the DRL network in figure 75. This frequency selection will obviously cause some interference problems at the nodal point (Headquarters). It should be possible (due to geographical configurations) to operate the path Power station - Headquarters - Training centre - Mt. High on the same frequencies. The other paths however will be investigated later in this chapter as we start with interference calculations. If the interference calculations show unacceptable interference levels, the frequency allocation must be modified on these paths. In some systems it would be preferable to select expensive antennas, adjust output levels and so on. In other systems frequency economy is not that important, so other RF-channels could be used.

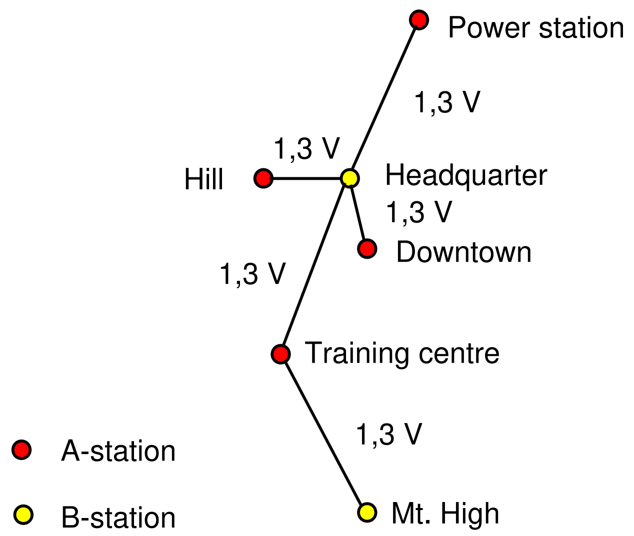


Figure 75 DRL-network with first frequency allocation.

To avoid overshoot problems, the polarization could be changed for every second path in general. This would give a reduction of interference level due to overshoot equal to the antenna cross-polarization discrimination. This has to be decided during the interference calculations.

14.2.3.3 Meshed networks

Special care must be taken if the DRL-network forms a ring as indicated in figure 76. If the number of stations in the ring is an even number, the ordinary allocation of A- and B-station may be used as indicated in figure 76a).

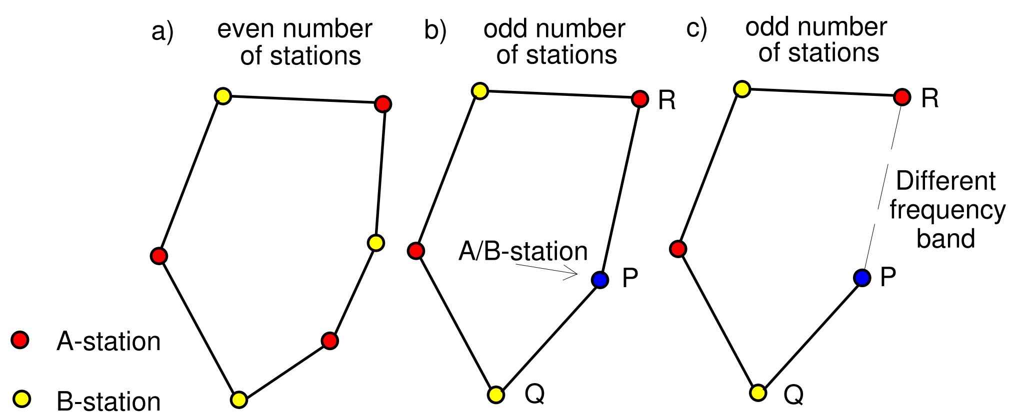


Figure 76 Meshed networks

An odd number of stations in a ring should generally be avoided and needs special considerations. If the same frequency band is used through the entire system (figure 76b), one of the stations must be an A/B-station. That is, this critical station P must transmit in both the lower and the upper frequency band. This may result in a reduced frequency separation between the transmitter and the receiver at the critical site. If a limited number of the radio channels are used, it is possible to achieve the necessary frequency separation between the transmitter and the receiver. Consider a 1+1 system operating in the upper 6 GHz frequency band. If channels 1 and 3 are used as transmit frequencies on the path P towards Q, channels 5' and 7' (or 6' and 8') could be used as transmit frequencies towards R. This gives a frequency separation of 80 MHz (120 MHz) between transmitter and receiver at P. Depending on the particular type of equipment, this may be sufficient to avoid interference problems. It must be verified that the interference level at the receiver is below the critical limit determined by the receiver characteristics.

Over-shoot interference is also more critical when A/B-stations are needed. Station Q will disturb station R (and vice versa) unless terrain obstructions or angle discrimination provide sufficient attenuation of the disturbing signal.

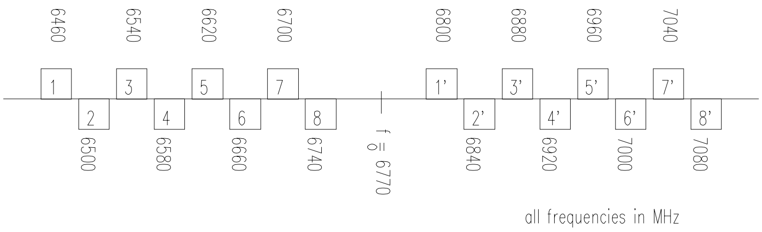


Figure 77 Upper 6 GHz frequency plan

Another solution is to use a different frequency band for one of the paths in the meshed network (figure 76c). The frequency separation between the transmitter and the receiver at the critical site will automatically be sufficiently large by this approach. If one of the paths is short (~ 10 km), using a high frequency band (e.g. 15 GHz) on this path could solve the frequency allocation problem.

Chapter

15

Interference calculations

15.1 Examples of RF-coupling

Figure 78 shows some typical examples of undesirable RF-coupling between radio channels in the same RF-band. The influence of the different types of interference depends on the network configuration, terrain obstructions, antenna types and radio equipment, etc.

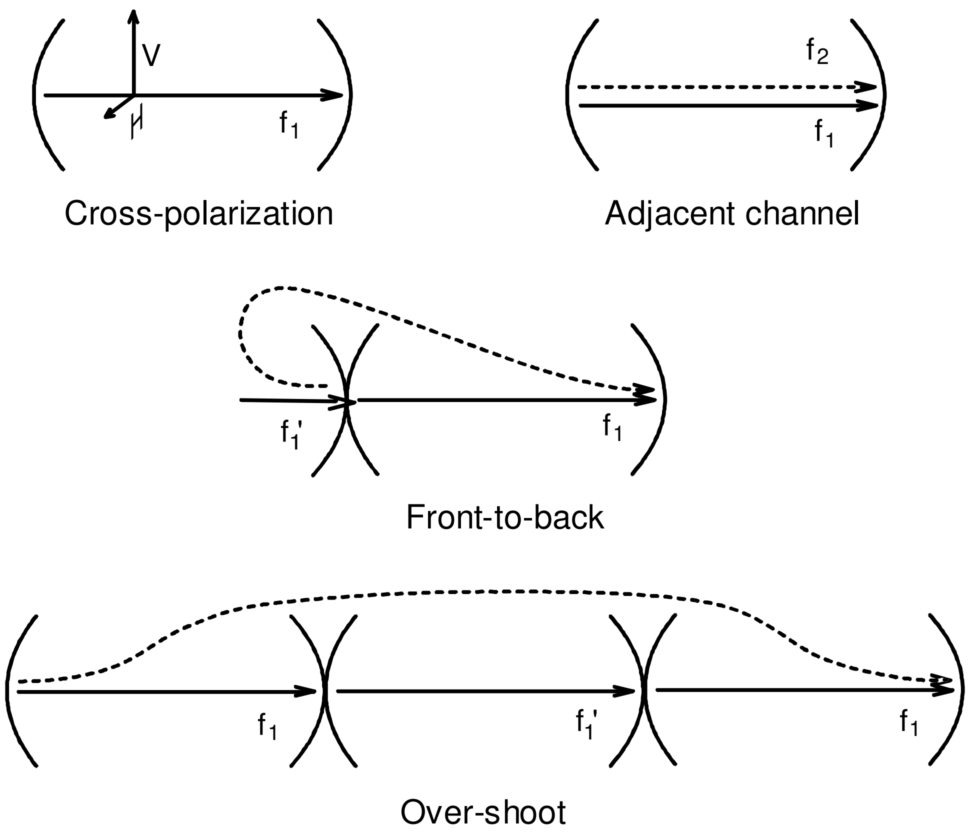


Figure 78 Undesirable RF-coupling between radio channels

Cross-polarization

The discrimination between channels operating on opposite polarization is mainly determined by the cross-polar discrimination of the antenna. De-polarization in the atmosphere, due to reflections or ray bending may also increase cross-polar interference,

Adjacent channel

The frequency separation, the channel filter at the receiver and the width of the transmitted spectrum determined the interference level. Opposite polarization is often used.

Front-to-back

The interference level is mainly a function of the antenna front-to-back ratio.

Over-shoot

If the paths are aligned as indicated in figure 78, interference due to over-shoot is critical. Use of opposite polarization or change of radio channels is recommended.

15.2 Calculation principles for digital networks

Channels with a channel separation ¤ ♎ can be excluded from the interference evaluations due to filter discrimination in the receiver.

There are generally two different ways to include the influence of interfering signals in the system performance calculations:

> Starting from a calculated interference level at the input of the disturbed receiver, and calculating the influence on the performance (degraded threshold level).
>
> Starting from an allowed interference level at the input of the disturbed receiver, and comparing it with the level of the interfering signal.

Only the first method will be described in this chapter.

The interference calculations are performed by calculating the interference level and determining the receiver threshold degradation (if any).

The simplified RL networks in figures 79 and 80 are used to illustrate the calculation procedure.

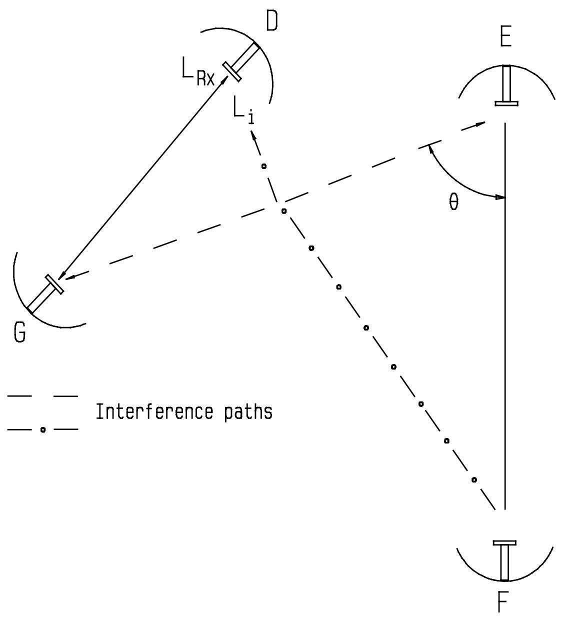


Figure 79 Rectangular network

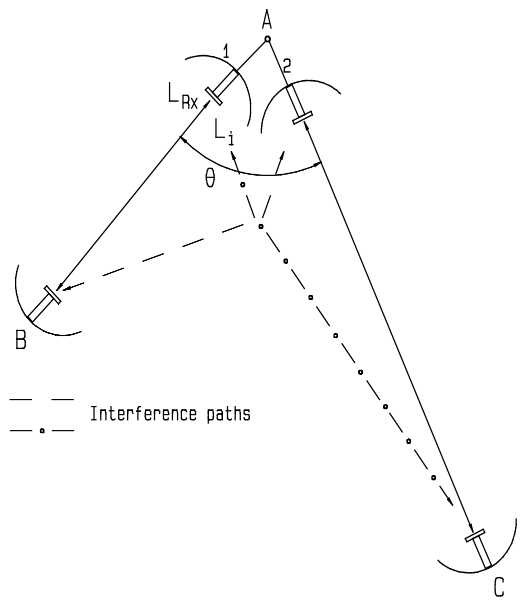


Figure 80 Triangular network

To illustrate the calculation principles figure 80 is used. Path A - B is assumed to be the disturbed path, and A - C the disturbing path.

The input level during fading free time at A1 (and at B) is L_{Rx}. The receiver threshold level (BER 10^{-3}) for an undisturbed receiver is L_{Te}. Figure 81 shows the receiver threshold level as a function of the interference level. For this particular radio L_{Te} = -73 dBm.

The interfering signal C -> A1 reaches the receiver A1 via antenna A1 with a level L_I. If more than one interfering signal has to be considered, L_I is the resulting level of the combined individual levels, L_{Ii}:

130) $$L_I = 10\log \sum_{i=1}^{n} 10^{(L_{Ii} - Aj)/10}$$

L_I ... combined level in dBm of all interfering signals.
L_{Ii} ... level in dBm of an individual interfering signal.
A_j ... adjacent-channel attenuation in dB of the interfering signal by the receiver.

From the diagram in figure 81, the degraded receiver threshold level, L_{TeI}, which corresponds to that interfering signal level, can be found.

The degraded receiver threshold level is approximated by the formula:

131) $$L_{TeI} \approx L_{Te} + 10\log\left(1 + 10^{((-L_{Te} + C_R + L_I)/10)}\right)$$

C_R ... Numeric constant reflecting the receiver's ability to withstand interference signals (normalised S/I-ratio).

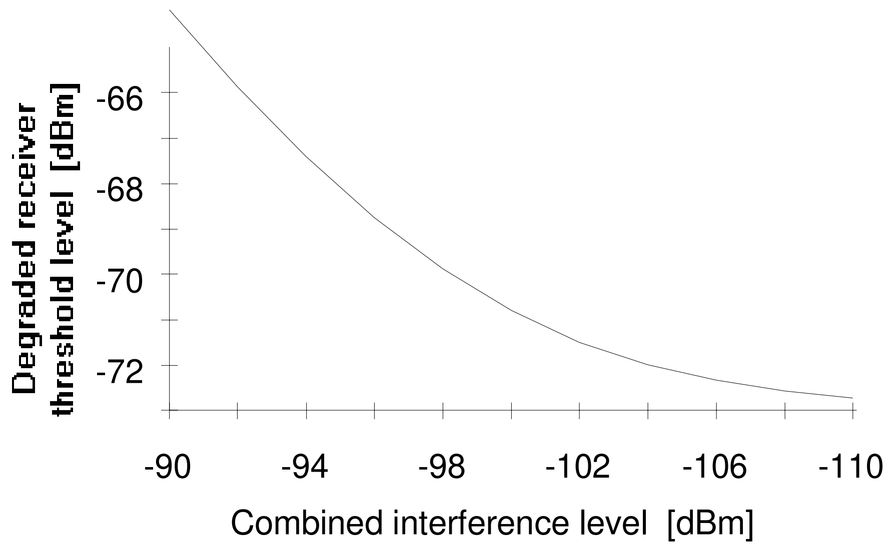


Figure 81 Degraded receiver threshold level as a function of combined interference level.

Example 2

Assume the combined interference level to be -100 dBm. Using figure 81, it can be seen that the degraded threshold level is -71 dBm That is a 2 dB threshold degradation of the system.

This new threshold level should be included in the system performance calculations. *The degradation of the receiver threshold level (and thus the fading margin of the system) by interfering signals means that the performance and availability predictions cannot be completed before that degradation has been investigated.*

The approach; starting from a given input level, has some disadvantages:

> If radio relay systems already exist in that RF-band and within the same geographical area, performance and availability predictions can first be carried out when all data concerning the systems involved are known.
>
> Each new RL has an impact on the performance and availability of the existing ones. To avoid a new RL degrading the performance and availability of the existing ones below the planning objectives, stringent requirements for discrimination of the new antennas may be necessary. For each additional link, the requirements will be more stringent, or new radio frequencies will have to be added.
>
> An interference level higher than the threshold level, L_{Te}, ($S/I = \infty$) may lock the receiver onto that interference signal in case its own transmitter at the opposite end breaks down. This may connect a subscriber onto a non-authorised conversation or data stream, and - in the case of frequency diversity - prevents the link from switching over to its diversity channel.

The first two disadvantages can be overcome by allowing for ample fading margin for the first links in a network, to give some "space" in their performance and availability for a future degradation.

Locking of a receiver onto an interfering signal can be avoided by planning for interference levels:

$$L_{Ii} < L_{Te}[S/I = \infty]$$

Starting from an allowed degradation of the receiver's threshold, the influence on the BER performance and availability can already be considered when starting the planning. The obtained interference levels will however always differ from the allowed ones. The performance and availability calculations have thus to be corrected, applying the obtained deterioration for L_{Te}.

15.3 Antenna selection

For paths sharing a common radio site, only the antenna in the nodal point contributes to the suppression of interfering signal with its back- and side-lobe attenuation. In fact, this is the only parameter that contributes.

The interfering signal, originated in the transmitter A1 (figure 83), and disturbing receiver C, is only attenuated by antenna A1. This allows the selection of an antenna type with the necessary discrimination. The formulas 132) through 135) give the necessary antenna discrimination .

15.3.1 Nodal station disturbs outstation

Ref. figure 83: Tx_{A1} --> Rx_C.

132) $$D_A = L_{TeI} + M_{FI} - L_{Ii} + \Delta G + \Delta L_{Tx}$$

D_A ... antenna discrimination in dB
ΔG ... difference in gain [dB] between the two antennas at the nodal point
ΔL_{Tx} ... difference in output level [dBm] of the wanted versus the disturbing signal
M_{FI} ... flat-fading margin in dB in the presence of:
L_{Ii} ... level of an individual interfering signal in dBm
L_{TeI} ... receiver threshold level in dBm in the presence of L_I (the combined level of all interfering signals)

15.3.2 Outstation disturbs nodal point

Ref. figure 83: Tx_C --> Rx_{A1}.

133) $$D_A = L_{TeI} + M_{FI} - L_{Ii} + \Delta G + \Delta L_{Rx}$$

ΔL_{Rx} ... difference in dB between the input levels for the stations in the nodal point

15.3.3 Optimal conditions

Optimal conditions with respect to D_A are achieved if

134) $$\Delta G = \Delta L_{Rx} = \Delta L_{Tx} = 0$$

That is the same gain used for all antennas in the nodal point, and the network is planned for identical transmitter output and receiver input levels in this nodal point.

The formulas 132) and 133) above can then be written as:

135) $$D_A = L_{TeI} + M_{FI} - L_{Ii}$$

No higher fading margin should be planned for than the performance objectives require (to minimise antenna costs).

These considerations are not absolutely correct if the involved paths have very different length (outage probability). The input level at the receiver on the longer path should then be higher than the other input level. The system should be designed for minimum outage probability for the paths involved.

15.3.4 Attenuation between antennas on the same tower

Normally the coupling between two antennas feed horns is most critical. To simplify the problem, only this coupling is calculated. If this distance between the two feed horns is greater than twenty times the wavelength, we can apply the normal formula for free-space attenuation:

136) $$A_F = 32.45 + 20 \cdot \log(f \cdot d_F)$$

A_F ... attenuation in dB between antennas installed on the same tower.
f ... radio frequency in GHz.
d_F ... distance between the two antennas in **m**, and $d_F \geq \lambda$. (figure 82)
λ ... wavelength in m.

This formula applies for all normal antenna installations at frequencies larger than 2 GHz. Notice that the attenuation in formula 136) is independent of the antennas' relative discrimination (back-to-back ratio, etc.). The exact attenuation has to be determined by measurements on the specific antenna type. If higher values are required, the size and type of the dish, the type of the radiator and the relative attitude have to be considered. The standard antenna diagrams are only valid in the antenna far field, and is thus not applicable in near field situations on the same tower.

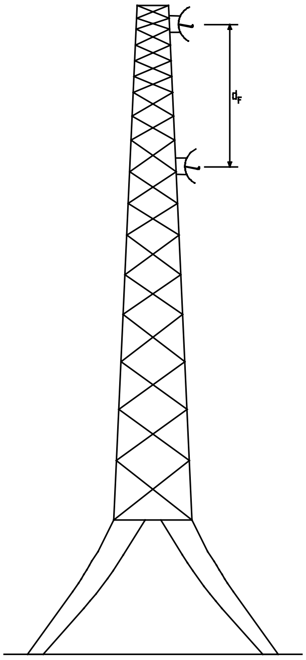


Figure 82 Attenuation between antennas on the same tower.

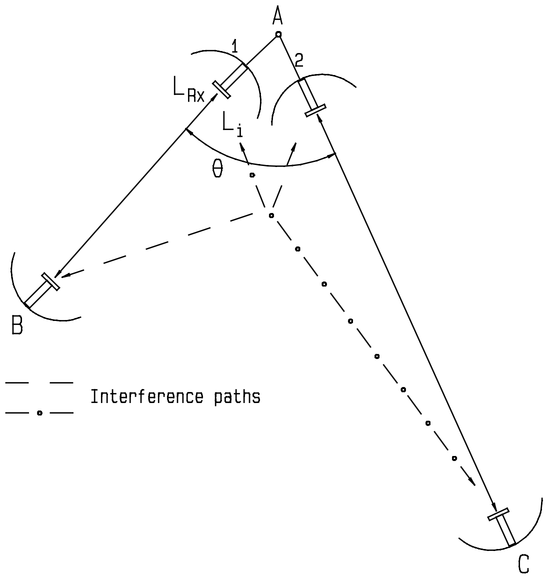


Figure 83 Simplified RL network (triangular configuration).

15.4 Calculation of interference signal level

15.4.1 General formula

The calculation of the interference levels, L_{Ii}, is discussed in this chapter. The formulas presented here are implemented in the Microsoft Excel spreadsheet for efficient calculations. The spreadsheet set-up also includes the threshold degradation calculations based upon the combined interference level (ref. formula 131). These formulas are included in the spread-sheet set-up.

The general formula for the calculation of interfering signal level for co-polar operation is (the wanted and interfering signals have the same polarization):

137) $$L_{Ii} = L_{Tx} - A_{Tx} + G_{Tx} - D_{TxCp} - A_{fs} - A_A + G_{Rx} - A_{Rx} - D_{RxCp}$$

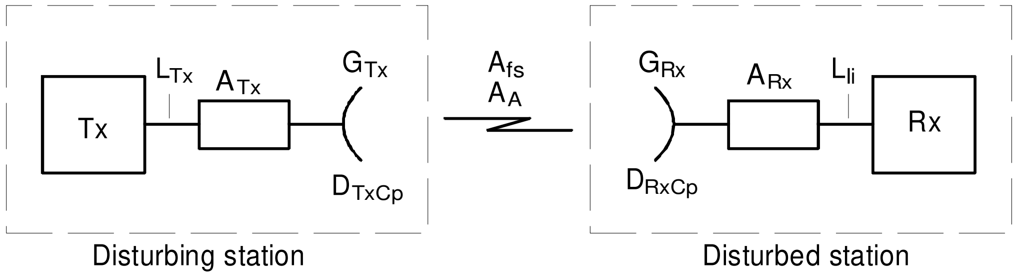


Figure 84 Interference model (co-polar operation)

This formula is more easily understood if it is divided in logical sub-formulas. The net output power from the interfering source towards the receiver of interest equals:

$$L_{Tx} - A_{Tx} + G_{Tx} - D_{TxCp}$$

The total attenuation of the unwanted signal at the receiver (except radio filters) equals:

$$G_{Rx} - A_{Rx} - D_{RxCp}$$

The general formula for the calculation of interfering signal level for X-polar operation is (the wanted and interfering signals have opposite polarization):

138) $$L_{Ii} = 10\log(10\text{^}((L_{Tx} - A_{Tx} + G_{Tx} - D_{TxXp} - A_{fs} - A_A + G_{Rx} - A_{Rx} - D_{RxCp})/10) + (10\text{^}((L_{Tx} - A_{Tx} + G_{Tx} - D_{TxCp} - A_{fs} - A_A + G_{Rx} - A_{Rx} - D_{RxXp})/10))$$

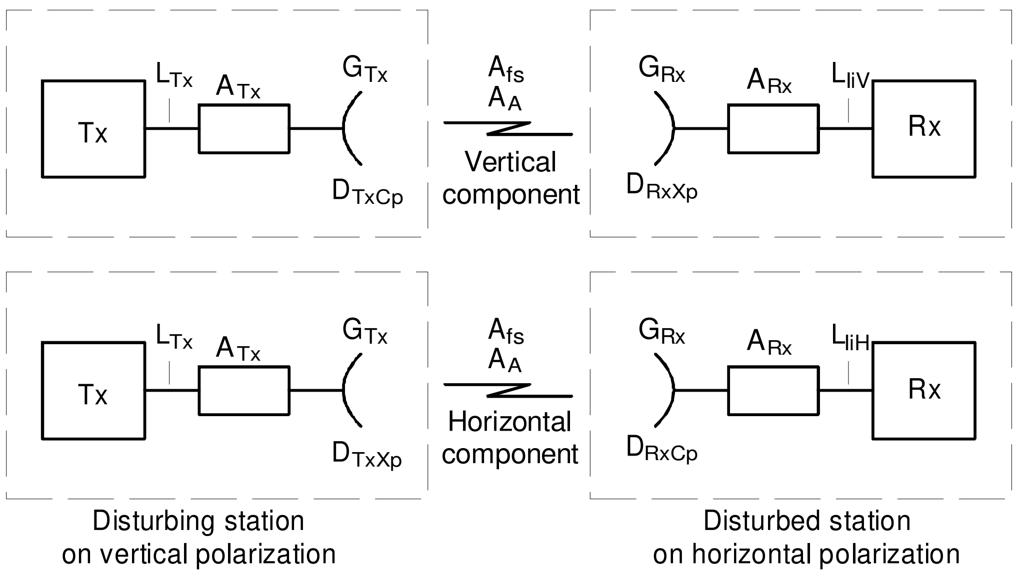


Figure 85 Interference model (cross-polar operation)

The disturbing station transmits the signal with opposite polarization to the disturbed station. The suppression of the cross-polar component in the transmitting antenna is not infinite. In the back-lobe direction most antennas have approximately the same radiation level for both polarizations; giving **no** cross-polar discrimination in that particular direction.

Consider the model in figure 85. The disturbing transmitter is transmitting both a vertical and a (smaller) horizontal component. The receiving antenna at the disturbed station will receive both polarizations, but the two components will generally experience a different discrimination in the receiving antenna. So, the received interference level at the disturbed station is the sum of a vertical and a horizontal component. In most cases one of the two components will dominate, depending on the relationship between D_{TxXp} and D_{RxXp} for the particular angles for a given path.

Again, splitting up the formula gives the following sub-equations:

The net output power of the co-polar signal component (referred to the receiver) from the disturbing station equals:

$$L_{Tx} - A_{Tx} + G_{Tx} - D_{TxXp}$$

The attenuation of this co-polar signal in the receiver is given by:

$$G_{Rx} - A_{Rx} - D_{RxCp}$$

The net output power of the cross-polar signal component (referred to the receiver) from the disturbing station equals:

$$L_{Tx} - A_{Tx} + G_{Tx} - D_{TxCp}$$

The attenuation of this cross-polar signal in the receiver is given by:

$$G_{Rx} - A_{Rx} - D_{RxXp}$$

Adding the input level of the co-polar and the cross-polar interference signal on a power basis gives the total interference level at the disturbed receiver.

The symbols used in the formulas are explained on the following page.

L_{Ii} : level of single interference signal in dBm.
L_{Tx} : output level of the disturbing transmitter in dBm.
A_{Tx} : waveguide/branching attenuation in dB in the transmitting station.
G_{Tx} : maximum antenna gain for the transmitting antenna in dB (disturbing station).
D_{TxCp} : co-polar antenna discrimination in dB for the transmitting station.
D_{TxXp} : X-polar antenna discrimination in dB for the transmitting station.
A_{fs} : free space attenuation in dB.
A_A : additional attenuation in dB due to non-clearance of the interference path, and/or RF attenuators for level adjustment.
G_{Rx} : maximum antenna gain for the receiving antenna in dB (disturbed station).
A_{Rx} : waveguide/branching attenuation in dB in the receiving station.
D_{RxCp} : co-polar antenna discrimination in dB for the receiving station.
D_{RxXp} : X-polar antenna discrimination in dB for the receiving station.

If more than one interfering signal is present, the total interference level, L_I, is obtained according to formula 131).

15.4.2 Formulas for triangular configuration

For triangular network configurations as in figure 80, the formulas 137) and 138) can be combined and simplified. When the paths of the interfering and wanted signals coincide, the following formulas can be used.

15.4.2.1 Nodal station disturbs outstation

Tx_{A1} -> Rx_C in figure 80.

139) $$L_{Ii} = L_{Rx} - A_G + \Delta G + \Delta L_{Tx}$$

L_{Rx} : input level of the wanted signal in dBm during fading free time.

A_G : antenna discrimination for the angle Θ in dB, for the antenna in the nodal station, referred to the antenna maximum gain.

ΔG : difference in gain in dB between the two antennas in the nodal point.
+ for larger gain of the disturbing transmitter's antenna.
- for smaller gain of the disturbing transmitter's antenna.

ΔL_{Tx} : difference in dB between the output power levels of the two transmitters (A1 and A2).
+ for larger output power of the disturbing transmitter (A1).
- for smaller output power level in A1.

Θ : angle between the wanted and the interfering signal.

15.4.2.2 Outstation disturbs nodal station

Tx_C -> Rx_{A1} in figure 80.

140) $$L_{Ii} = L_{Rx} - A_G + \Delta G + \Delta L_{Rx}$$

ΔG : difference in gain in dB between the two antennas in the nodal point.
+ for larger gain of the disturbed receiver's antenna.
- for smaller gain of the disturbed receiver's antenna.

ΔL_{Rx} : difference in dB between the input levels for the wanted signal at the disturbed receiver (A1) and the receiver subordinated to the disturbing transmitter (A2). The levels refer to fading free time (nominal input levels).
+ for lower input level at the disturbed receiver (A1).
- for higher input level at A1.

The other parameters have their previous definitions.

15.4.2.3 Optimal conditions

If the network is planned for equal antennas, receiver and transmitter levels at the nodal point, $(\Delta G = 0, \Delta L_{Tx} = 0, \Delta L_{Rx} = 0)$ the above formulas 139) and 140) can be written as:

141) $$L_{Ii} = L_{Rx} - D_A$$

The interference level simply equals the input level of the wanted signal minus the antenna discrimination. This implies that the antenna discrimination (as a rule of thumb) should be larger than the sum of the fading margin and the required S/I-ratio to avoid threshold degradation.

15.5 Calculation procedure

The explanation of the calculation procedure is based on a "case study" introduced in figure 86. This case will be used throughout this chapter.

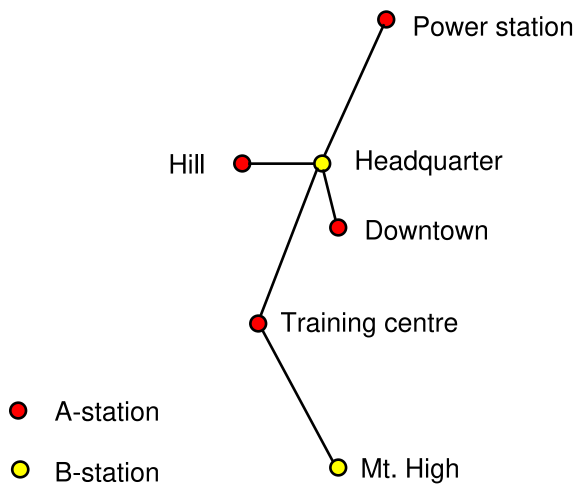


Figure 86 Radio-relay network

15.5.1 Preconditions

To rationalise the work, the following aids are recommended:

<u>Network diagram</u>

Network diagram, drawn to scale and angle, including all radio-relay circuits within the frequency band concerned, existing, planned and future extensions. Mark out the RF channel numbers, polarizations and sub-band labelling. (See figure 86.)

If the site locations are available in co-ordinate values, a program calculating the distance and angles between stations could be of great help.

<u>Network data</u>

Network data, such as antenna types, antenna radiation patterns (figures 87 - 90), transmitter output power, receiver threshold levels, predicted receiver input levels and waveguide attenuation.

<u>RL equipment interference data</u>

RL equipment interference data are normally given as diagrams:

Digital to digital interference diagrams.
Digital to analogue interference diagrams.
Analogue to digital interference diagrams.
(Analogue to analogue is not of interest in this document.)

Adjacent-channel attenuation as a function of the channel spacing.

The Excel spreadsheet set-up includes numerical calculations of these parameters.

Antenna radiation patterns

Antenna radiation patterns for all types of antennas used in the network should be available. For automatic interference calculations, the antenna diagrams should be available in a data base, matching the interference calculation program.

15.5.2 Interference calculations on digital network

The interference calculations are explained by examining the digital network in figure 86. Let us assume that every possible interference path contributes. The number of interfering paths is then:

142) $N = 2 \cdot m \cdot (m-1) = 2 \cdot m \cdot n$

Each receiver is disturbed by

143) $n = m - 1$

interfering signals

m ... total number of RL paths.
N ... total number of interfering paths in the network.
n ... total number of interfering paths for one receiver.

For a total of 5 RL paths (figure 86) we get:

$$n = 5 - 1 = 4 \quad \text{and} \quad N = 2 \cdot 5 \cdot 4 = 40$$

Equipment data

Nera digital radio link equipment will be used in these calculations.

NL195

```
Capacity:             140 Mb/s
Radio frequency:      6770 MHz
Transmitter power:    29 dBm
Branching loss:       1.2 dB  (1+1 system)
Receiver threshold:      -73 dBm (BER 10^-3)
Receiver threshold:      -69 dBm (BER 10^-6)

Adjacent channel separation:
Common antenna:       80 MHz for parallel polarization
                      40 MHz for cross polarization
```

Antenna data can be found in figures 87 through 90.

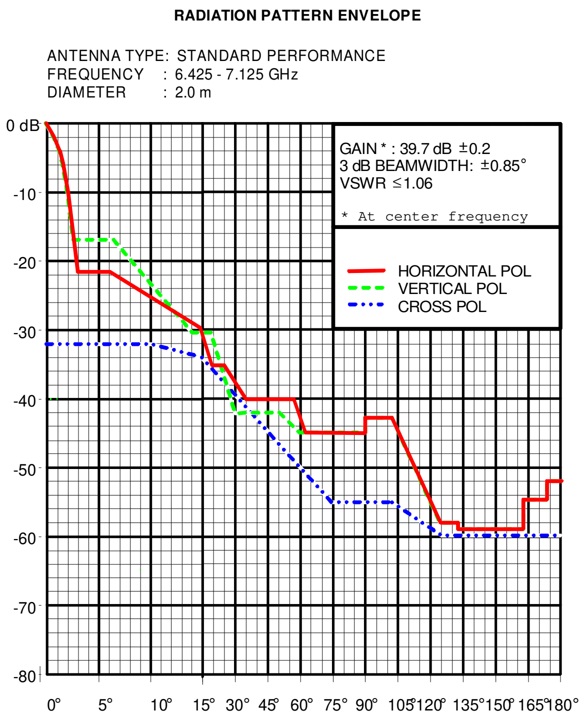


Figure 87 RPE 2.0m SP antenna

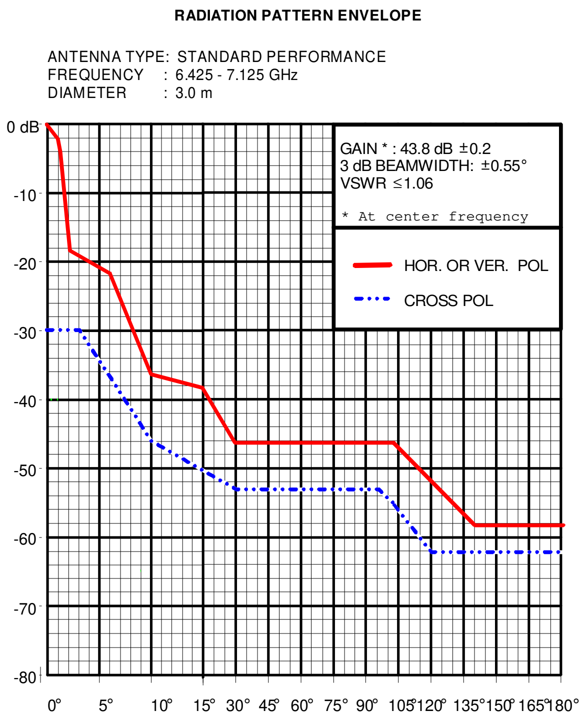


Figure 88 RPE 3.0m SP antenna

15.5.2.1 Interference evaluations

In principle, it would be necessary to check each antenna discrimination in the nodal stations for all disturbances. Initially, only the most critical interference path (intelligent guess) has to be examined. The result of this check gives an idea about the interference problems for the system in total. Assuming that figure 86 is drawn in scale, the path Headquarters - Training centre is most likely to be the critical path in this system.

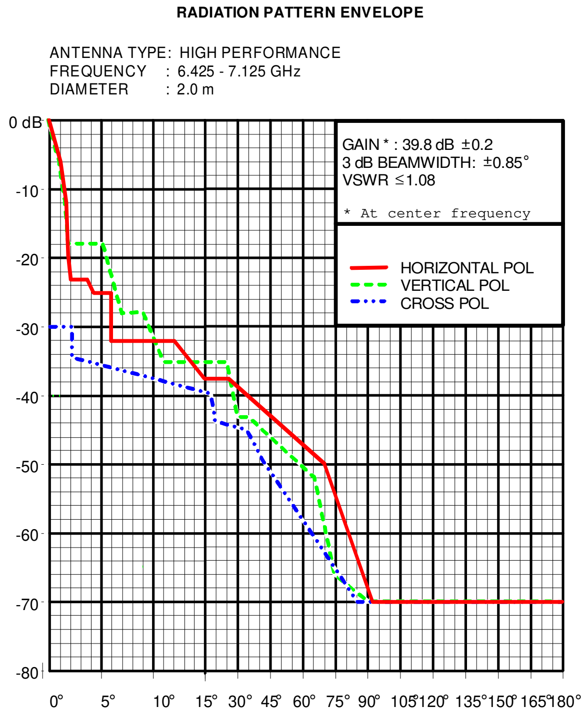


Figure 89 RPE 2.0m HP antenna

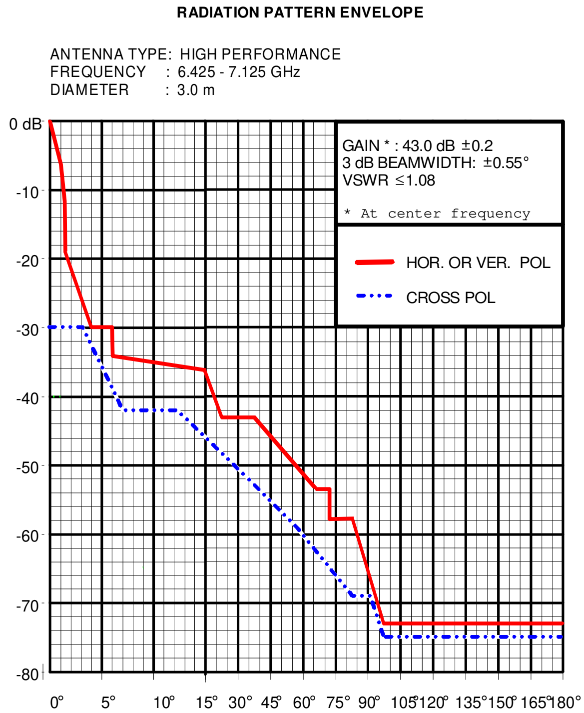


Figure 90 RPE 3.0m HP antenna

Figure 86 is redrawn in this section to include some more details.

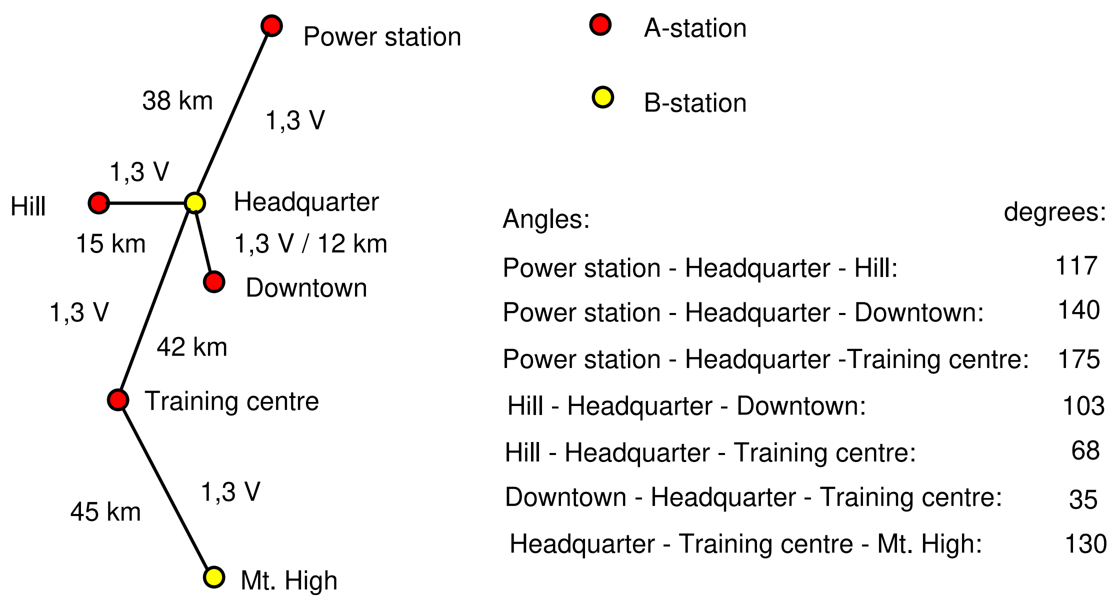


Figure 91 DRL-network with first frequency allocation.

The following evaluation starts with an unrealistic frequency plan. This is done to show the reader the influence of the interference sources involved, as well as the effect of the different countermeasures suggested during the evaluation. It should therefore be noted that figure 91 does not show the first frequency allocation presented by a trained system designer.

As a start, standard performance antennas are used, and no level adjustments are made to reduce interference problems. This gives a "worst case" evaluation. The interference calculations are performed using Excel spreadsheet, including some extra steps in the print-out to give some check-points for the reader.

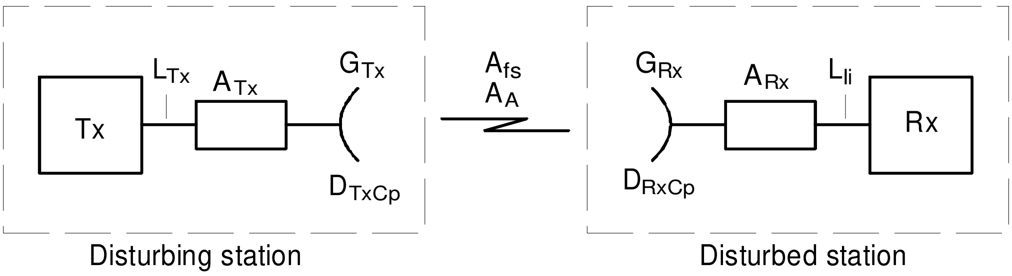
Path Headquarters - Training centre

Training centre	towards	Head-	quarter						
Interference from		Hill ->	Head	Down ->	Head	Power->	Head	Train->	High
Item	Unit	C-pol	X-pol	C-pol	X-pol	C-pol	X-pol	C-pol	X-pol
Frequency	GHz	6.77	6.77	6.77	6.77	6.77	6.77	6.77	6.77
Distance	km	15	15	12	12	38	38	42	42
Tx output power	dBm	29	29	29	29	29	29	29	29
Antenna gain Tx	dB	40.3	40.3	40.3	40.3	43.6	43.6	43.6	43.6
Losses Tx	dB	2.3	2.3	2.5	2.5	3	3	3	3
Dir. discr. Tx (pol)	dB	0	30	0	30	0	30	55	62
Net power out	dBm	67	37	66.8	36.8	69.6	39.6	14.6	7.6
Space loss int.	dB	132.5	132.5	130.6	130.6	140.6	140.6	141.5	141.5
Rx input level (nom)	dBm	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9
Antenna gain Rx	dB	43.6	43.6	43.6	43.6	43.6	43.6	43.6	43.6
Losses Rx	dB	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
Dir. discr. Rx (pol)	dB	46	53	46	53	55	62	0	30
Interference level	dBm	-71.0	-78.0	-69.3	-76.3	-85.5	-92.5	-86.4	-93.4
S/I (no fading)	dB	38.1	45.1	36.4	43.4	52.6	59.6	53.5	60.5
Threshold 1E-3	dBm	-73	-73	-73	-73	-73	-73	-73	-73
Threshold 1E-6	dBm	-69	-69	-69	-69	-69	-69	-69	-69
S/I BER 1E-3	dB	-2.0	5.0	-3.7	3.3	12.5	19.5	13.4	20.4
S/I BER 1E-6	dB	2.0	9.0	0.3	7.3	16.5	23.5	17.4	24.4

Headquarters	towards	Training	centre						
Interference from		Head ->	Hill	Head ->	Down	Head ->	Power	High ->	Train
Item	Unit	C-pol	X-pol	C-pol	X-pol	C-pol	X-pol	C-pol	X-pol
Frequency	GHz	6.77	6.77	6.77	6.77	6.77	6.77	6.77	6.77
Distance	km	42	42	42	42	42	42	45	45
Tx output power	dBm	29	29	29	29	29	29	29	29
Antenna gain Tx	dB	40.3	40.3	40.3	40.3	43.6	43.6	43.6	43.6
Losses Tx	dB	2.5	2.5	3	3	3.8	3.8	2.1	2.1
Dir. discr. Tx (pol)	dB	53	55	45	45	55	62	0	30
Net power out	dBm	13.8	11.8	21.3	21.3	13.8	6.8	70.5	40.5
Space loss int.	dB	141.5	141.5	141.5	141.5	141.5	141.5	142.1	142.1
Rx input level (nom)	dBm	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9	-32.9
Antenna gain Rx	dB	43.6	43.6	43.6	43.6	43.6	43.6	43.6	43.6
Losses Rx	dB	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Dir. discr. Rx (pol)	dB	0	30	0	30	0	30	54	62
Interference level	dBm	-87.4	-89.4	-79.9	-79.9	-87.4	-94.4	-85.3	-93.2
S/I (no fading)	dB	54.5	56.5	47.0	47.0	54.5	61.5	52.4	60.3
Threshold 1E-3	dBm	-73	-73	-73	-73	-73	-73	-73	-73
Threshold 1E-6	dBm	-69	-69	-69	-69	-69	-69	-69	-69
S/I BER 1E-3	dB	14.4	16.4	6.9	6.9	14.4	21.4	12.3	20.2
S/I BER 1E-6	dB	18.4	20.4	10.9	10.9	18.4	25.4	16.3	24.2

The path Training centre towards Headquarters will be used to explain the set-up. The most critical interference comes from the disturbing path Downtown towards Headquarters. The interference level is calculated both for co-polar and cross-polar operation to introduce the procedures.

Co-polar operation



L_{Tx}	29.0	dBm
A_{Tx}	2.5	dB
G_{Tx}	40.3	dB
D_{TxCp}	0.0	dB

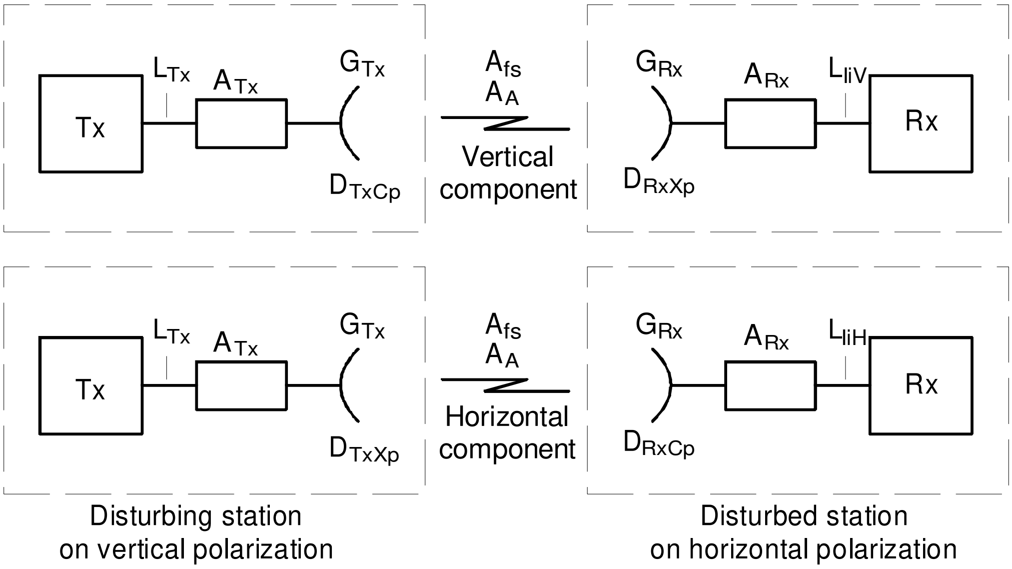
G_{Rx}	43.6	dB
D_{RxCp}	46.0	dB
A_{Rx}	3.1	dB

Figure 92 Calculation example (co-polar operation)

The distance from Downtown to Headquarters is 12 km giving a free space loss $A_{fs} = 130.6\text{dB}$ at 6.77 GHz. The values given in figure 92 give an interference level $L_{Ii} = -69.3\text{dBm}$ for co-polar operation:

$$L_{Ii} = L_{Tx} - A_{Tx} + G_{Tx} - D_{TxCp} - A_{fs} + G_{Rx} - D_{RxCp} - A_{Rx} = -69.3\text{dBm}$$

Cross-polar operation



L_{Tx}	29.0	dBm
A_{Tx}	2.5	dB
G_{Tx}	40.3	dB
D_{TxCp}	0.0	dB
D_{TxXp}	30.0	dB

G_{Rx}	43.6	dB
D_{RxCp}	46.0	dB
D_{RxXp}	53.0	dB
A_{Rx}	3.1	dB

Figure 93 Calculation example (cross-polar operation)

Let us assume that the path Training Centre towards Headquarters operates on vertical polarization and Downtown - Headquarters on horizontal.

Vertical component

The disturbing station (Downtown) is transmitting on horizontal polarization, so the vertical component is the cross-polar component at this station. Consequently the antenna discrimination at the transmitter equals D_{TxXp}. Similarly, vertical polarization is the co-polar component at the receiver, so the antenna discrimination equals D_{RxCp}. The vertical component of the interfering signal is found by:

$$L_{IiV} = L_{Tx} - A_{Tx} + G_{Tx} - D_{TxXp} - A_{fs} + G_{Rx} - D_{RxCp} - A_{Rx} = -99.3\,\text{dBm}$$

Horizontal component

The horizontal component is the co-polar component at the transmitting station Downtown. Consequently the antenna discrimination at the transmitter equals D_{TxCp}. Horizontal polarization is the cross-polar component at the receiver, so the antenna discrimination equals D_{RxXp}. The horizontal component of the interfering signal is found by:

$$L_{IiH} = L_{Tx} - A_{Tx} + G_{Tx} - D_{TxCp} - A_{fs} + G_{Rx} - D_{RxXp} - A_{Rx} = -76.3\,\mathrm{dBm}$$

The horizontal component is the dominating part of the interfering signal, so the total interference level $L_{Ii} = -76.3\,\mathrm{dBm}$ for cross-polar operation.

Figure 81 shows that the combined interference level should be less than approximately -105 dBm to avoid any threshold degradation (< 1 dB degradation). The interference calculations show that the interference level is much higher, even with opposite polarizations on the different paths. It is also evident that it is almost impossible to achieve the required S/I ratio only by use of better antennas. Use of HP antennas would give typically 10 dB improvement in antenna discrimination. Use of SHXP antennas gives almost the necessary discrimination, but at a rather high cost.

This preliminary interference study shows that it is necessary to use other RF-channels on some of the paths from the nodal station Headquarters. It is also preferable to use different polarizations on some of the critical paths.

The system is supposed to be expandable (up to 3+1) in the future. This restricts the use of radio channels, and it is desirable to use the same frequencies as far as possible.

Countermeasures

The interference problems may be reduced by decreasing the output power on the short paths from Headquarters towards Hill and Downtown. It is desirable to have approximately the same input level on all receivers in a nodal point. Inserting a 6 dB attenuator at the transmitter on these two shorter paths would almost balance the input levels at the nodal point.

Using high performance antennas at all radios in Headquarter, allows us to use the same frequency on the main route (high front-to-back ratio), and also the same frequency on the two shorter hops. Keeping the SP-antennas at Training centre, forces us to change RF-channels on the path Training centre - Mt. High. To reduce possible interference problems with the paths Hill - Headquarters - Downtown, the polarization is unchanged (vertical). Figure 94 shows the network with the new frequency allocations.

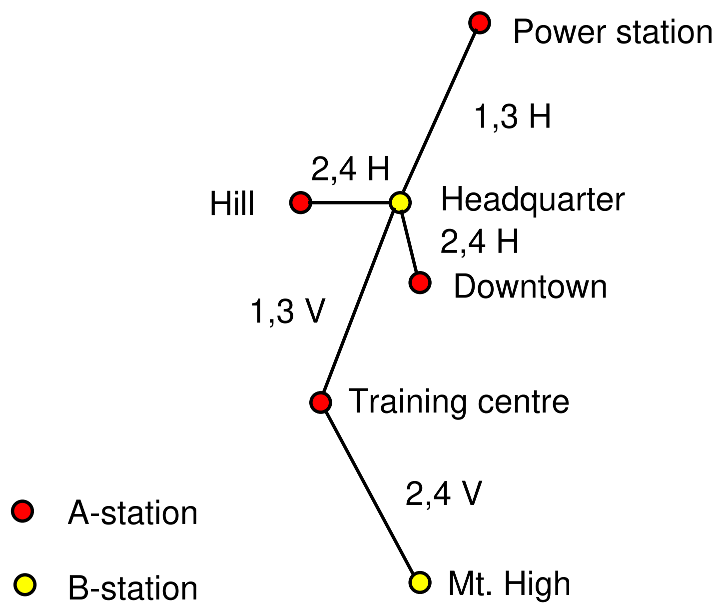


Figure 94 DRL-network with second frequency allocation.

The resulting interference calculations show reduced interference levels on all of the critical paths. The receiver threshold levels are summarised in table 15. The threshold degradation is limited to ~1 dB.

Path	Output	Threshold 1E-3
Power station - Headquarters	29.0 dBm	-72.3 dBm
Hill - Headquarters	19.0 dBm	-71.9 dBm
Downtown - Headquarters	19.0 dBm	-71.9 dBm
Headquarters - Training centre	29.0 dBm	-72.3 dBm
Training centre - Mt. High	29.0 dBm	-73.0 dBm

Table 15 Threshold levels with reduced interference levels.

15.5.2.2 Summary of interference calculations

Having performed the interference calculations after suggesting the necessary countermeasures, it is time to summarise the resulting system.

Countermeasures

The interference calculations verified the need for high performance antennas at Headquarter. It was also necessary to use another pair of radio channels on the two shorter paths (Hill - Headquarters - Downtown). A 10 dB reduction of the output power level at these shorter paths was also suggested. This could be a permanent power reduction or an adaptive reduction using Automatic Transmit Power Control (ATPC).

15.6 The frequency plan

The frequency allocation is indicated in figure 94 as support for the interference calculations. The frequency plan is normally presented in another form as shown in figure 95.

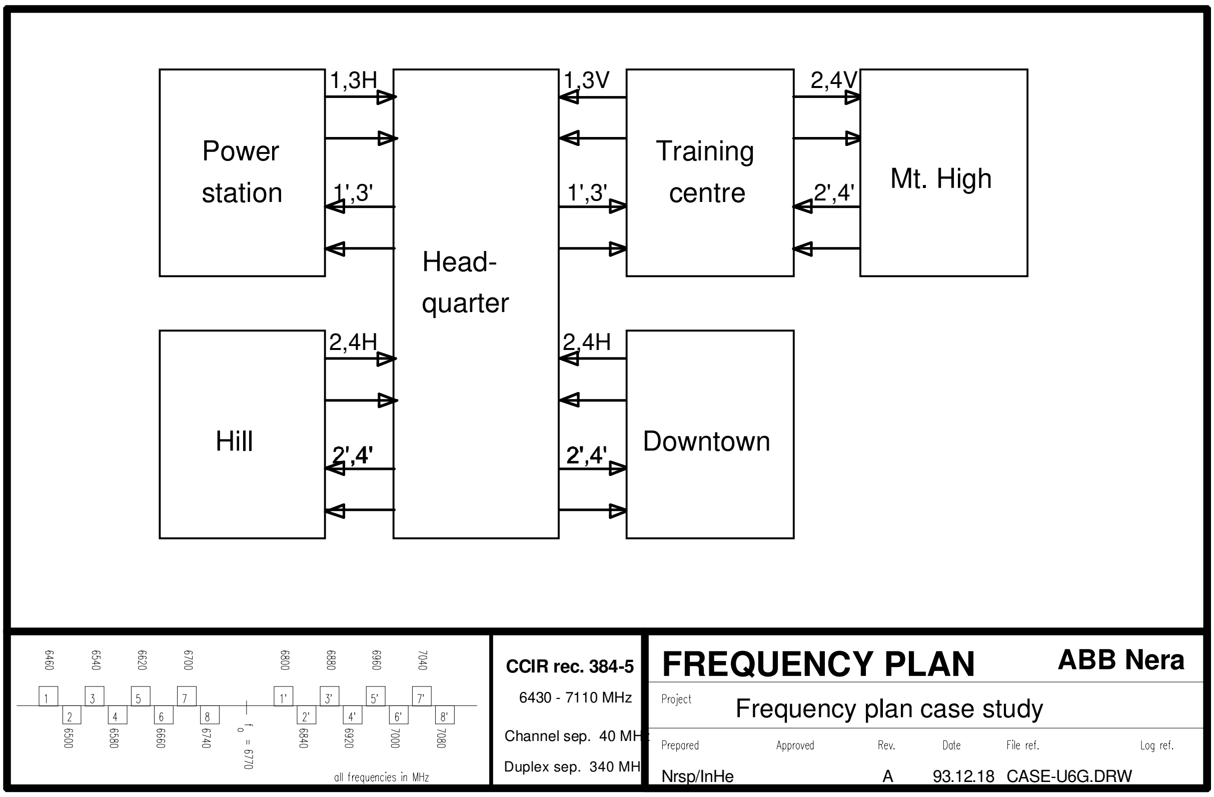


Figure 95 Frequency plan for case study.

Chapter

16

Reliability

The total unavailability of a radio path is the sum of the probability of hardware failure and unavailability due to rain. This chapter will cover unavailability due to hardware failures. It should be noted that the unavailability for the equipment has to be considered for both the *go* and the *return* direction, that is twice the calculated value. The probability that electronic equipment fails in service is not constant with time. Figure 96 shows that initial failures results in a higher probability of failures during the burn-in period. Similarly, wear-out failures give higher probability during the wear-out period. We will concentrate on the useful lifetime where random failures give a constant probability.

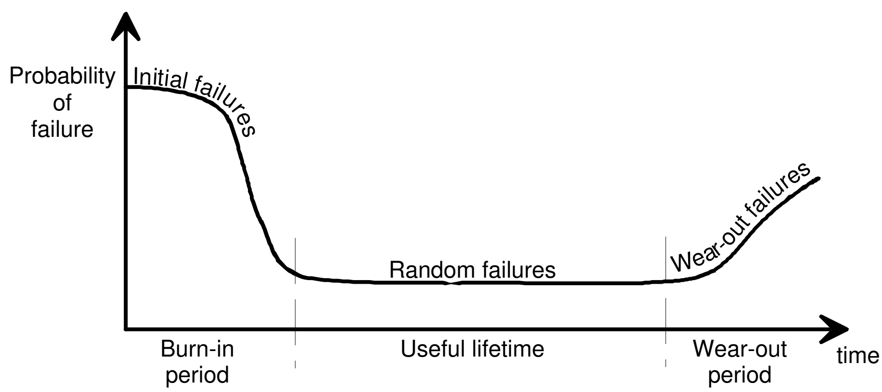


Figure 96 Failure probability

16.1 Equipment failure rate

After the burn-in period, the equipment failure rate is assumed to be constant until the wear-out period starts, and the equipment reliability can be predicted using analytical methods.

If the failure rate is λ, the probability of m failures when testing n equipment modules in a unit time is given by the binominal distribution:

144) $$p_m = \frac{n!}{m!(n-m)!}\lambda^m(1-\lambda)^{n-m}$$

The mean value of this distribution is

145) $$\sum_{m=0}^{n} p_m \cdot m = n \cdot \lambda$$

The average number of surviving equipment modules after one unit time is thus

146) $$N_{avg} = n - n \cdot \lambda$$

The variation of number of surviving equipment modules with time is given by

147) $$n + \frac{dn}{dt} = n - n \cdot \lambda$$

Solving this equation, it is possible to find how the number of surviving equipment modules varies with time on average.

148) $$\frac{dn}{dt} = -n \cdot \lambda; \qquad n = n_0 \cdot e^{-\lambda t}$$

$n_0 =$ inital number of equipment modules

A constant failure rate gives an exponential decrease of surviving equipment modules.

16.2 MTBF of modules

If the failure rate per unit time equals λ, the average time between failures is given by

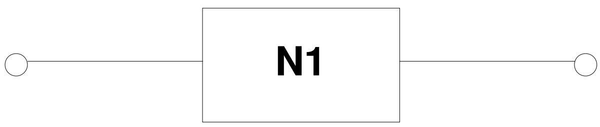
$$149) \qquad \lambda \cdot \Delta t = 1 \qquad \Delta t = \frac{1}{\lambda}$$

Δt is called *MTBF* (Mean Time Between Failures). *MTBF* is more convenient to use than λ when calculating unavailability.

16.3 Calculation of unavailability

16.3.1 Unavailability of one equipment module

The unavailability of one equipment module is given by



$$150) \qquad N_1 = \frac{MTTR}{MTBF + MTTR}$$

where *MTTR* (Mean Time To Repair) is the expected time before the failure has been repaired. For telecommunication equipment $MTBF >> MTTR$ and equation 150) may be approximated by $N_1 \approx \frac{MTTR}{MTBF}$.

<u>Example:</u>

Transmitter group 140 Mb/s - 64 QAM

$MTBF = 125000$ hours $MTTR = 10$ hours

$$N_1 = \frac{10}{125000 + 10} \approx \frac{10}{125000} = 8 \cdot 10^{-5}$$

16.3.2 Unavailability of cascaded modules

The system in figure 97 will be available only if all the modules are available simultaneously.

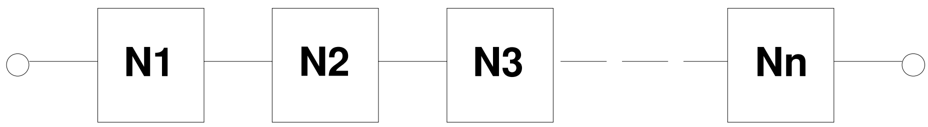


Figure 97 Cascaded modules

The availability of the total system will be

151) $$A_s = \prod_{i=1}^{n} A_i = \prod_{i=1}^{n} (1 - N_i)$$

The corresponding unavailability is given by

152) $$N_s = 1 - A_s = 1 - \prod_{i=1}^{n} (1 - N_i) \approx 1 - \left(1 - \sum_{i=1}^{n} N_i\right) = \sum_{i=1}^{n} N_i$$

So, when the unavailability is much smaller than the availability, the unavailability of a system of cascaded modules is the sum of the unavailabilities of its individual modules.

16.3.3 Unavailability of parallel modules

To improve the system availability, modules may be connected in parallel. The system will then be unavailable only if all the modules are unavailable simultaneously.

The unavailability is given by

153) $$N_s = \prod_{i=1}^{n} N_i$$

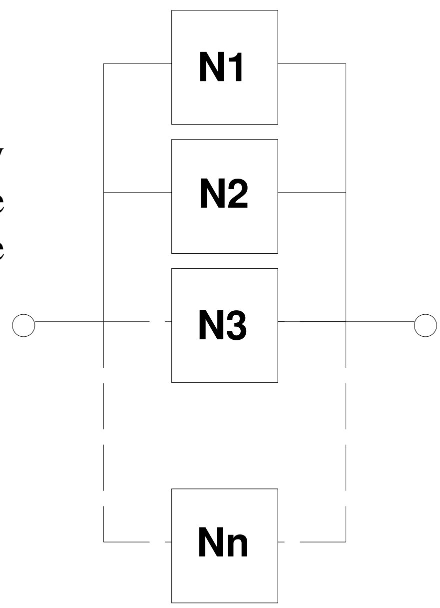


Figure 98 Parallel modules

16.3.4 Unavailability of a n+1 redundant system

In telecommunication equipment a n+1 redundant system is often used both to improve system performance due to atmospherical disturbances and to reduce system unavailability. A protected channel is unavailable if two of the unprotected channels are unavailable. It is assumed that the probability for more than two channels to be unavailable is negligible.

If the unavailability of the unprotected channels all equals *N*, the unavailability of one protected channel is given by

154) $$N_{n+1} = \frac{1}{n}\left(\frac{(n+1)!}{2!((n+1)-2)!}\right)N^2(1-N)^{(n+1)-2}$$

For telecommunication equipment the unavailability is much smaller than the availability, and equation 154) may be approximated by $N_{n+1} \approx \frac{n+1}{2}N^2$.

<u>Example:</u>

NL190 64QAM 140 Mb/s

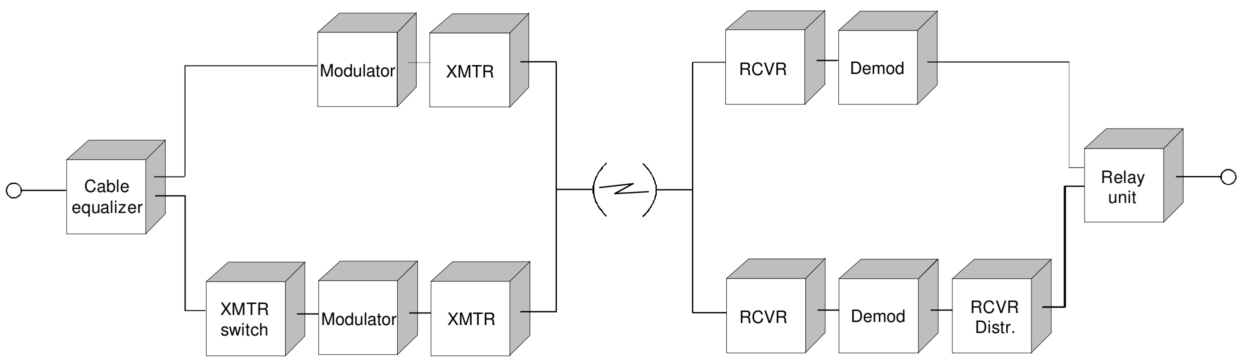


Figure 99 Simplified block diagram

The block diagram above shows a one-way radio hop in a 1+1 system configuration. The MTBF values for the modules in the system are given in table 16.

Module	MTBF	Failure rate
Cable equalizer	830 000 hours	$1.2 \cdot 10^{-6}$
Modulator	375 000 hours	$2.7 \cdot 10^{-6}$
Transmitter	290 000 hours	$3.5 \cdot 10^{-6}$
Receiver	200 000 hours	$5.0 \cdot 10^{-6}$
Demodulator	315 000 hours	$3.2 \cdot 10^{-6}$
Relay unit	3 300 000 hours	$0.3 \cdot 10^{-6}$
Transmitter switch	555 000 hours	$1.8 \cdot 10^{-6}$
Receiver distribution unit	830 000 hours	$1.2 \cdot 10^{-6}$

Table 16 MTBF values

The failure rates for the two redundant paths are

$$\lambda_{r1} = (2.7 + 3.5 + 5.0 + 3.2) \cdot 10^{-6} = 14.4 \cdot 10^{-6}$$

$$\lambda_{r2} = (1.8 + 2.7 + 3.5 + 5.0 + 3.2 + 1.2) \cdot 10^{-6} = 17.4 \cdot 10^{-6}$$

The failure rate for common units:

$$\lambda_c = (1.2 + 0.3) \cdot 10^{-6} = 1.5 \cdot 10^{-6}$$

Mean time to repair: $MTTR = 3$ hours for all units.

The corresponding unavailabilities will then be:

$$N_{r1} \approx MTTR \cdot \lambda_{r1} = 4.32 \cdot 10^{-5} \qquad N_{r2} \approx MTTR \cdot \lambda_{r2} = 5.22 \cdot 10^{-5}$$

$$N_c \approx MTTR \cdot \lambda_c = 4.5 \cdot 10^{-6}$$

The equipment unavailability is thus

$$N_e = N_c + (N_{r1} \cdot N_{r2}) = 4.50226 \cdot 10^{-6}$$

Comparing the values of N_e with N_c clearly indicated that the unprotected modules in the system dominate the equipment unavailability.

The path unavailability and availability are

$$N_p = 2 \cdot N_e = 9 \cdot 10^{-6} \qquad \text{(or 4½ minute/year)}$$

$$A_p = 1 - N_p = 0.999991 \qquad \text{(or 99.9991\%)}$$

References

[1] CCITT Rec. G.801. Digital Transmission models. CCITT Volume III - Fascicle III.5, Geneva 1989.

[2] CCITT Rec. G.821. Error Performance of an International Digital connection forming part of an Integrated Services Digital Network. CCITT Volume III - Fascicle III.5, Geneva 1989.

[3] ITU-T Rec. G.826, "Error Performance Parameters and Objectives for International, Constant Bit Rate Digital Paths at or above the Primary Rate", 08/96.

[4] ITU-T Rec. G.827, "Availability Parameters and Objectives for International, Constant Bit Rate Digital Paths at or above the Primary Rate", 08/96.

[5] ITU-R Rec. F.557-4. Availability objective for radio-relay systems over a hypothetical reference circuit and a hypothetical reference digital path, Geneva 1997.

[6] ITU-R Rec. 594-4. Error performance objectives of the hypothetical reference digital path for radio-relay systems providing connections at a bit rate below the primary rate and forming part or all of the high grade portion of an integrated services digital network, Geneva 1997.

[7] CCITT Rec. I.411. ISDN User-Network Interfaces - Reference Configurations. CCITT Volume III - Fascicle III.8, Geneva 1989.

[8] ITU-R Rec. F.696-2. Error performance and availability objectives for hypothetical reference digital sections forming part or all of the medium-grade portion of an integrated services digital network connection at a bit rate below the primary rate utilizing digital radio-relay systems, Geneva 1997.

[9] ITU-R Report 1052-1. Error Performance and Availability Objectives for Digital Radio-Relay Systems used in the Medium Grade Portion of an ISDN Connection. Reports of the ITU-R, Annex to Volume IX-Part 1, Geneva 1990.

[10] ITU-R Rec. 697-2. Error performance and availability objectives for the local-grade portion at each end of an integrated services digital network connection at a bit rate below the primary rate utilizing digital radio-relay systems, Geneva 1997.

[11] ITU-R Report 1053-1. Error Performance and Availability Objectives for Digital Radio-Relay Systems used in the Local-Grade Portion of an ISDN Connection. Reports of the ITU-R, Annex to Volume IX-Part 1, Geneva 1990.

[12] S. H. Lin, T. C. Lee, M. F. Gardina: "Diversity Protections for Digital Radio - Summary of Ten-Year Experiments and Studies". IEEE Communications Magazine, February 1988 - Vol. 26, No.2.

[13] W. D. Rummler: "A Statistical Model of Multipath Fading on a Space Diversity Radio Channel".

[14] W.D. Rummler, "A new selective fading model: Application to propagation data". The Bell System Technical Journal, vol. 58, No. 5, May-June 1979, pp. 1037-1071.

[15] W. D. Rummler: "A Rationalized Model for Space and Frequency Diversity Line-of-Sight Radio Channels". Bell Laboratories, Holmdel, New Jersey 07733 (IEEE 1983).

[16] "Prediction of Transmission Quality on Digital L.O.S. Radio Relays", ABB Nera, September 9. 1992.

[17] E. Damosso, R. Failli: "Space and frequency diversity in digital radio: experimental results", CSELT Technical reports - Vol. XIII - No. 2 - April 1985.

[18] Propagation data and prediction methods required for terrestrial line-of-sight systems. Report 338-6. Reports of the ITU-R., 1990. Annex to volume V. Propagation in non-ionised media. Geneva ISBN 92-61-04211-2.

[19] Attenuation by atmospheric gases. ITU-R recommendation P.676-3, Geneva 1997.

[20] Water vapour: surface density and total columnar content. ITU-R recommendation P.836-1, Geneva 1997.

[21] Characteristics of precipitation for propagation modelling, P.837-1, Geneva 1994.

[22] R. W. Hubbard: "Angle Diversity Reception for L.O.S. Digital Microwave Radio", U.S. Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences, Boulder, CO 90303.

[23] Lin, Ginger, Alley: "Angle Diversity on Line-of-Sight Microwave Paths Using Dual-Beam Dish Antennas", AT&T Bell Laboratories, Andover, MA, ICC '87.

[24] ITU-R Rec. F.634-4: Error performance objectives for real digital radio-relay links forming part of the high-grade portion of international digital connections at a bit rate below the primary rate within an integrated services digital network. Geneva 1997.

[25] ITU-R recommendation F.1092-1. Error performance objectives for constant bit rate digital path at or above the primary rate carried by digital radio-relay systems which may form part or all of the international portion of a 27 500 km hypothetical reference path. Geneva 1997.

[26] ITU-R recommendation F.1189-1. Error performance objectives for constant bit rate digital path at or above the primary rate carried by digital radio-relay systems which may form part or all of the national portion of a 27 500 km hypothetical reference path. Geneva 1997.

[27] Availability objectives for real digital radio-relay links forming part of a high-grade circuit within an integrated services digital network. Recommendation 695. Recommendations of the ITU-R. 1990, Volume IX - part 1. Fixed service using radio-relay systems. Geneva ISBN 92-61-04251-1.

[28] Radio meteorological data. Report 563-4. Reports of the ITU-R., 1990. Annex to volume V. Propagation in non-ionised media. Geneva ISBN 92-61-04211-2.

[29] Effects of propagation on the design and operation of line-of-sight radio-relay systems. Report 784-3. Reports of the ITU-R., 1990. Annex to volume IX - part 1. Fixed service using radio-relay systems. Geneva ISBN 92-61-04251-1.

[30] Attenuation by hydrometeors, in particular precipitation, and other atmospheric particles. Report 721-3. Reports of the ITU-R., 1990. Annex to volume V. Propagation in non-ionised media. Geneva ISBN 92-61-04211-2.

[31] Propagation data and prediction methods required for the design of terrestrial line-of-sight systems. ITU-R Recommendation P.530-7, Geneva 1997.

[32] Characteristics of precipitation for propagation modelling. ITU-R Recommendation P.837-1, Geneva 1994.

[33] Heinz Karl: "The frequency planning of radio-relay networks" Radiolänk - projektering - workshop 1988-04-24

[34] Heinz Karl: "The planning and engineering of radio-relay networks" Radiolänk - projektering - workshop 1988-09-13

[35] Radio Regulations, ITU, Geneva 1990, ISBN 92-61-04141-8.

[36] ITU-R, XVIIth PLENARY ASSEMBLY, Düsseldorf 1990, Vol. IX.

[37] ITU-R, XVIIth PLENARY ASSEMBLY, Düsseldorf 1990, Vol. V.

[38] Martin P. M. Hall: "Effects of the troposphere on radio communication", IEE Electromagnetic waves series 8. London ISBN 0 86341 086 3.

[39] Roger G. Barry, Richard J. Chorley "Atmosphere, Weather & Climate" 6. edition. Routledge, ISBN 0-415-07761-3.

[40] Henri Sauvageot "Radar Meteorology", Artech House, Boston, London ISBN 0-89006-318-4.

[41] Dennis Roddy and John Coolen: "Electronic communications", Prentice-Hall International Editions, USA 1984, ISBN 0-13-250440-5.

[42] A.A.R. Townsend: "Digital line-of-sight radio links", Prentice Hall, Great Britain 1988, ISBN 0-13-212622-2.

[43] "REG 024 Measurement programme", ABB Nera 1993.

[44] "Propagation Measurements Ilfracombe - St. Hilary", ABB Nera 1994.

[45] "XPD Measurements Chasseral - Geneva, 96.02.08 - 98.03.31, Final report", Nera 1998.

[46] David K. Cheng: "Field and Wave Electromagnetics", Addison-Wesley Publishing Company 2. edition 1989, ISBN 0-201-52820-7.

[47] Adolf J. Giger: "Low-Angle Microwave Propagation: Physics and Modelling", Artech House 1991, ISBN 0-89006-584-5

[48] ITU-R Rec. 384-5. Radio-frequency channel arrangements for medium and high capacity analogue or high capacity digital radio-relay systems operating in the upper 6 GHz band. Recommendations of the ITU-R, Volume IX-Part 1, Geneva 1990, ISBN 92-61-04251-1.

[49] ITU-R Rec. 746. Radio-frequency channel arrangements and spectrum utilization. 1992 - Recommendations of the ITU-R, New and revised as of 8 March 1992, Geneva 1992, ISBN 92-61-04531-6.

[50] ITU-R Rec. 452-5. Prediction procedure for the evaluation of microwave interference between stations on the surface of the earth at frequencies above about 0.7 GHz. 1992 - Recommendations of the ITU-R, New and revised as of 8 March 1992, Geneva 1992, ISBN 92-61-04531-6.

[51] ITU-R Rec. F.1397. Error performance objectives for real digital radio links used in the international portion of a 27 500 km hypothetical reference path at or above the primary rate, Geneva 1999.

Appendix A

P_L-contour maps (ITU-R rep. 563-4 [28])

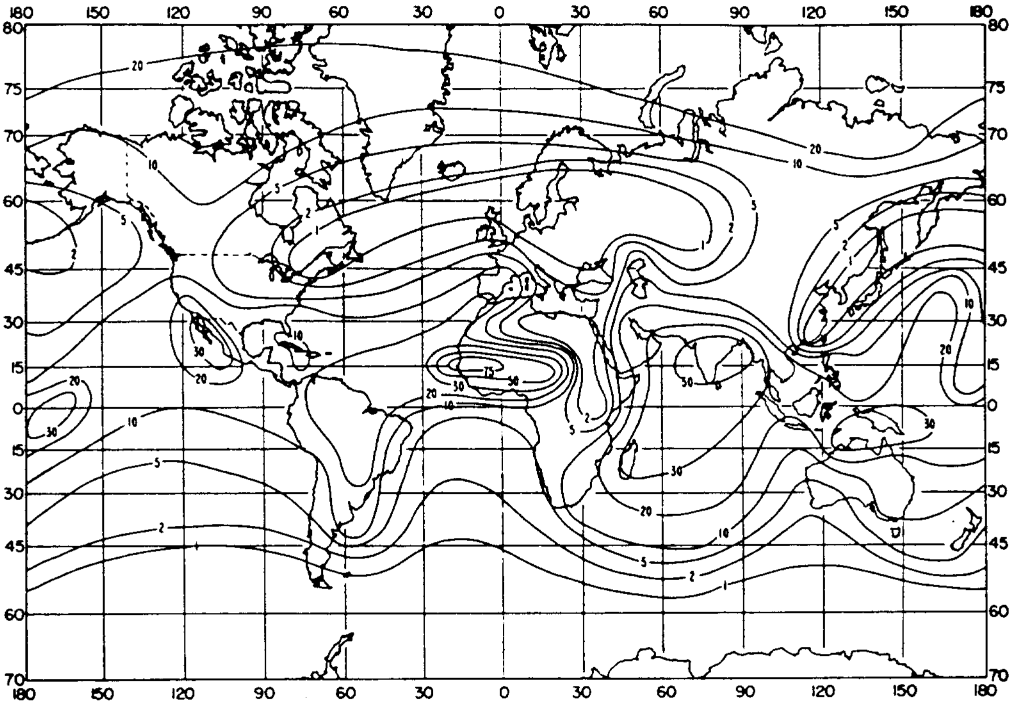


Figure A1 Percentage of time gradient $\le -100\,(N/\mathrm{km})$: February

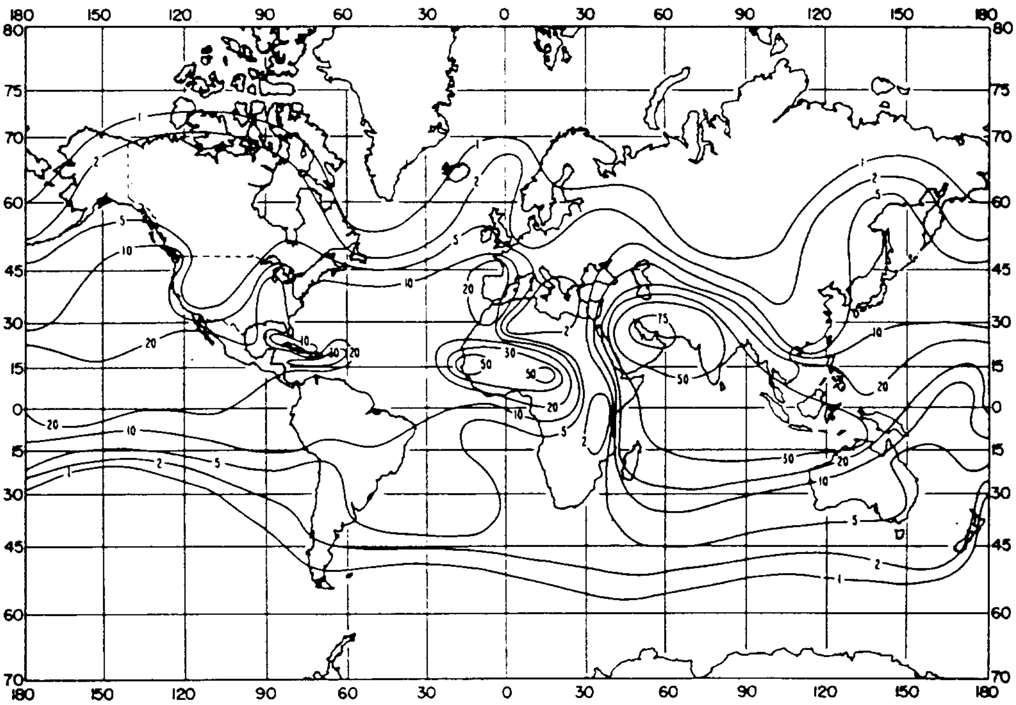


Figure A2 Percentage of time gradient $\le -100\,(N/\mathrm{km})$: May

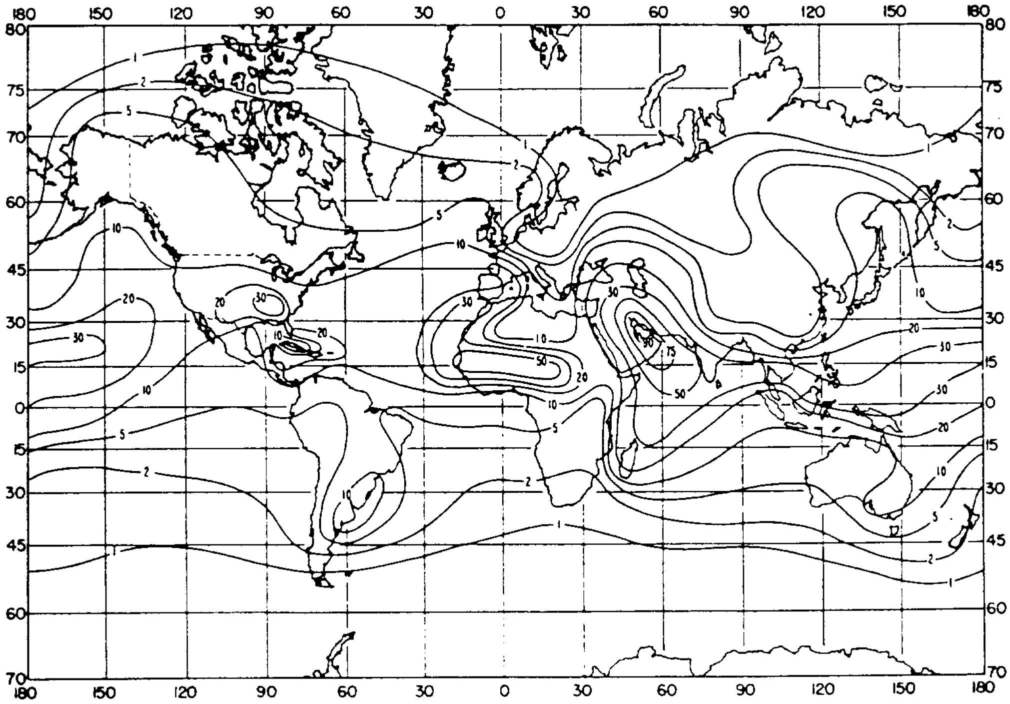


Figure A3 Percentage of time gradient $\leq -100\,(N\,/\,\mathrm{km})$: August

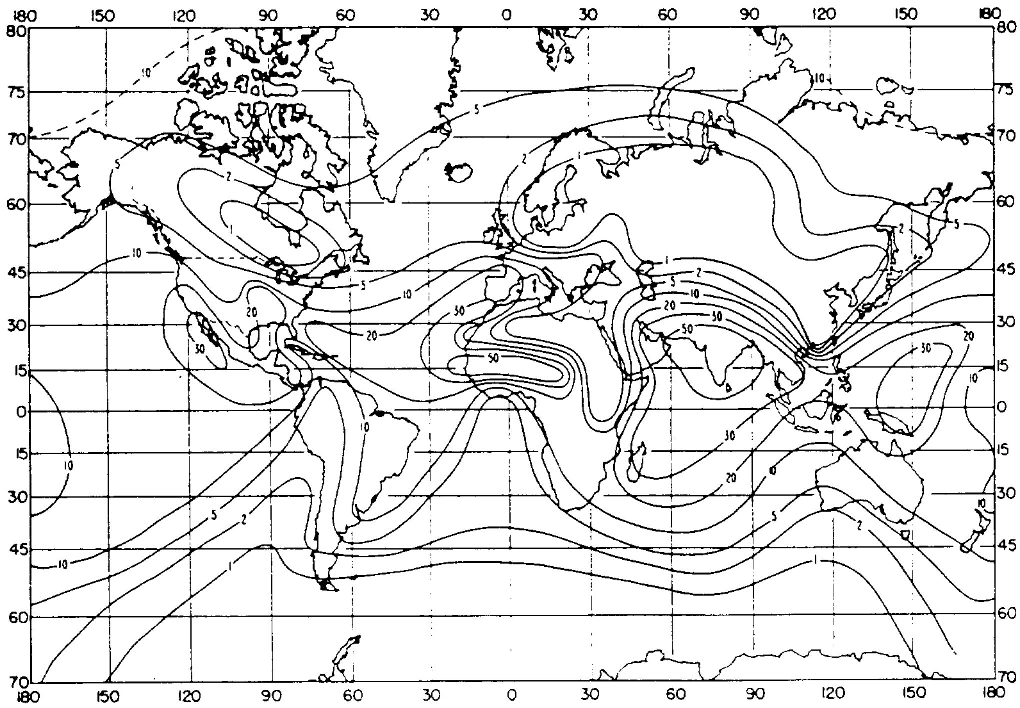


Figure A2 Percentage of time gradient $\leq -100\,(N\,/\,\mathrm{km})$: November

Appendix B

Rain zone contour maps (ITU-R rec. 837-1 [21])

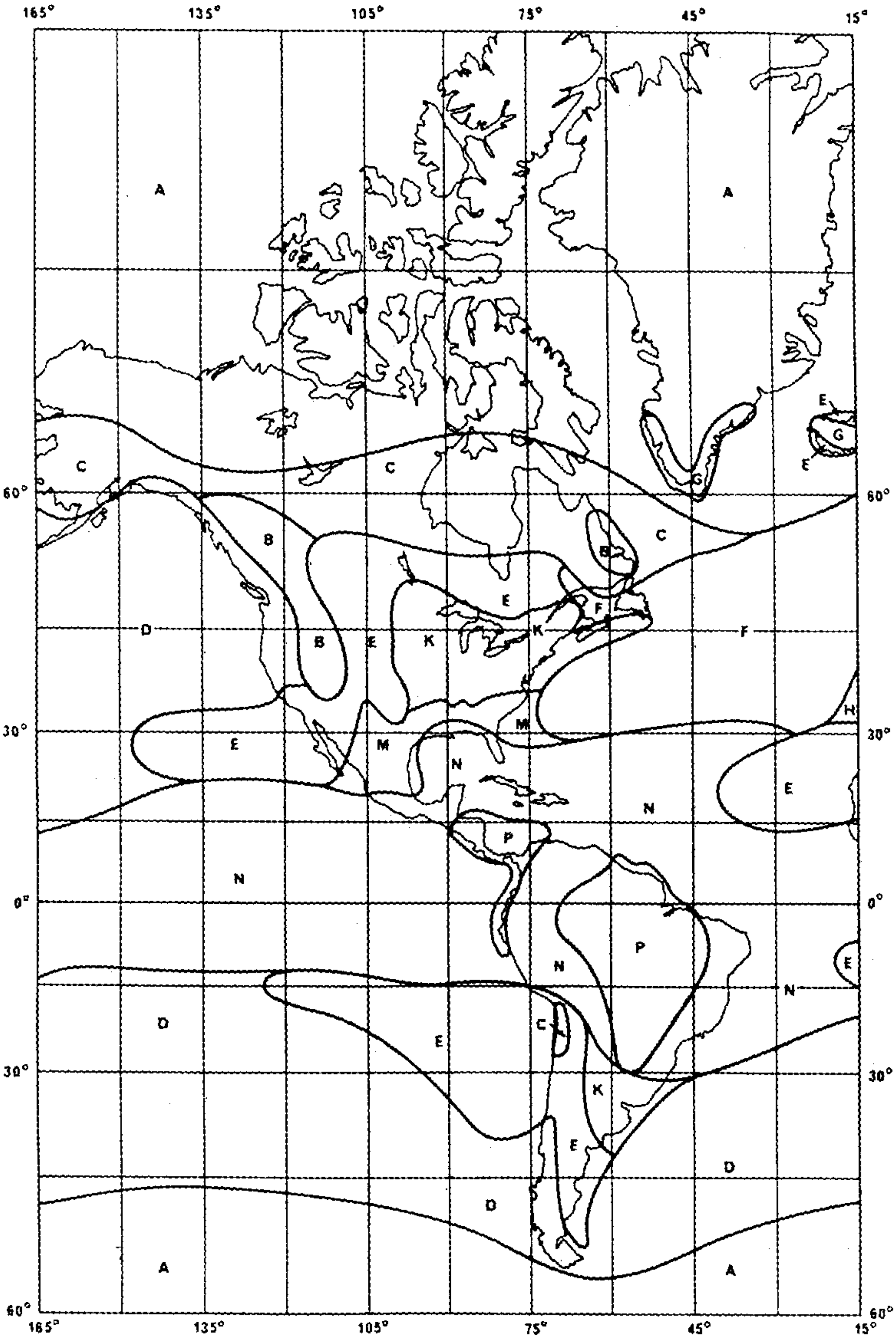


Figure B1 Rain zone contours (Americas)

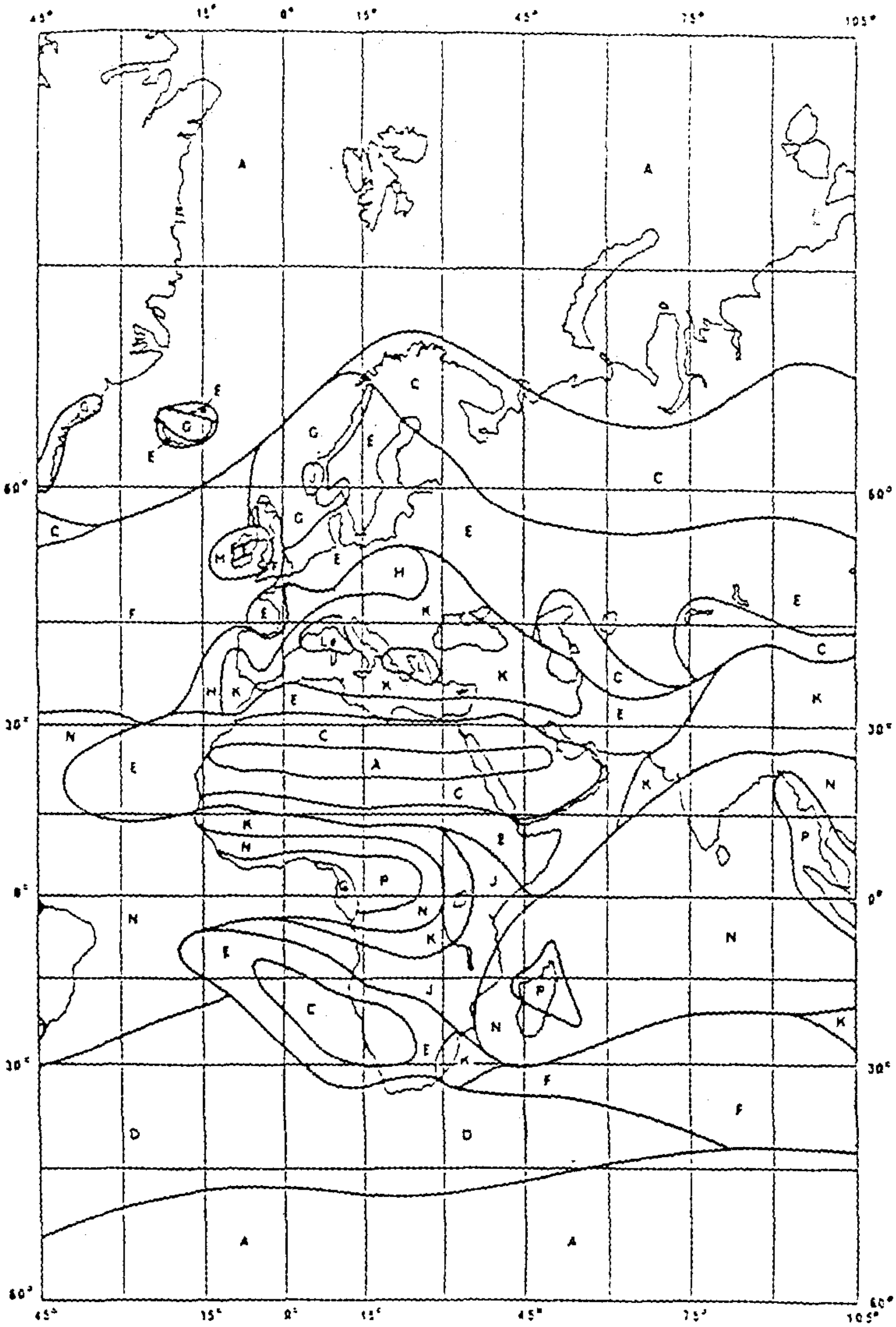


Figure B2 Rain zone contours (Europe and Africa)

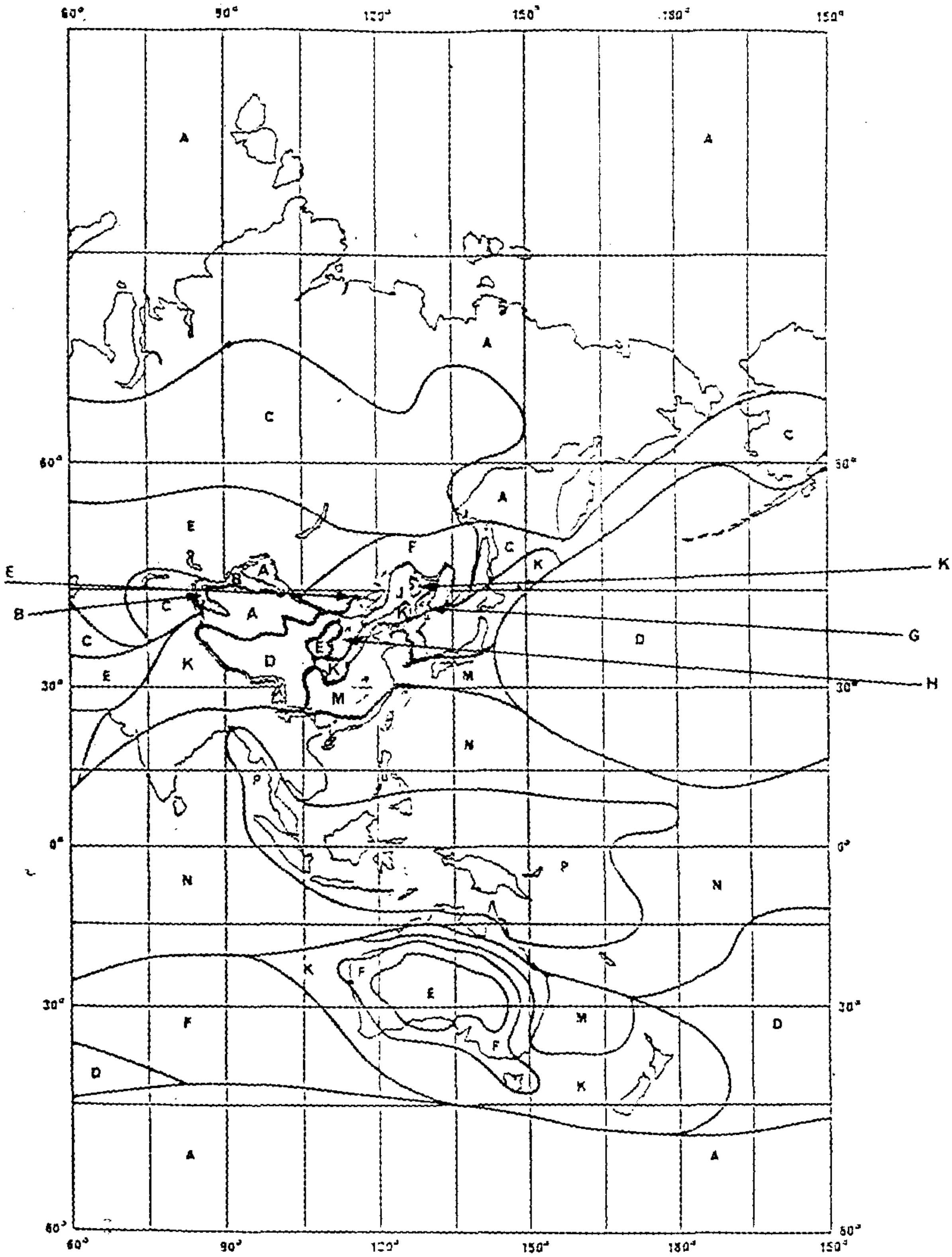


Figure B3 Rain zone contours (Far East)

Appendix C

Rainfall contour maps (ITU-R rep. 563-4 [28])

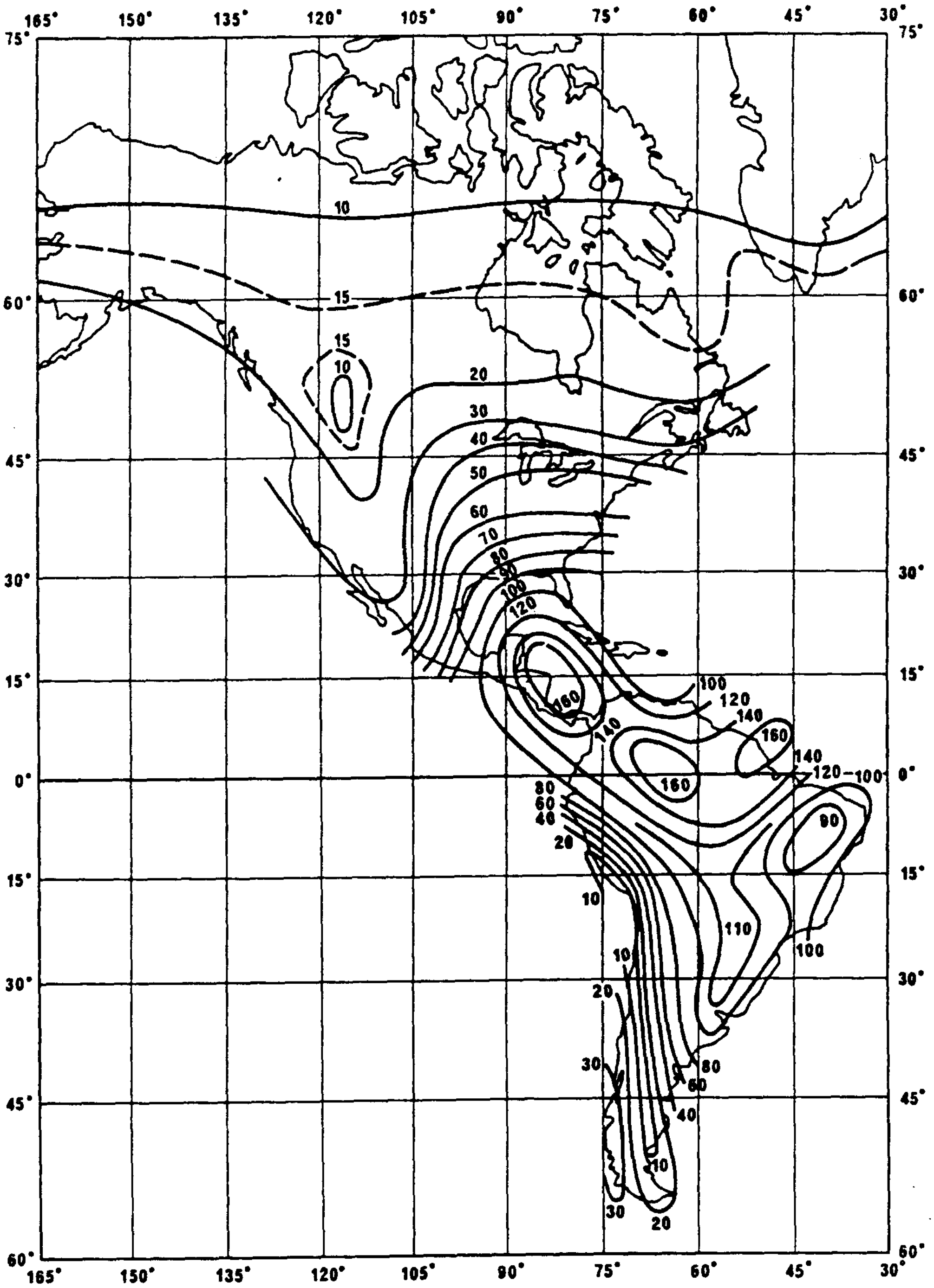


Figure C1 Rainfall contours for 0.01% of the time (Americas)

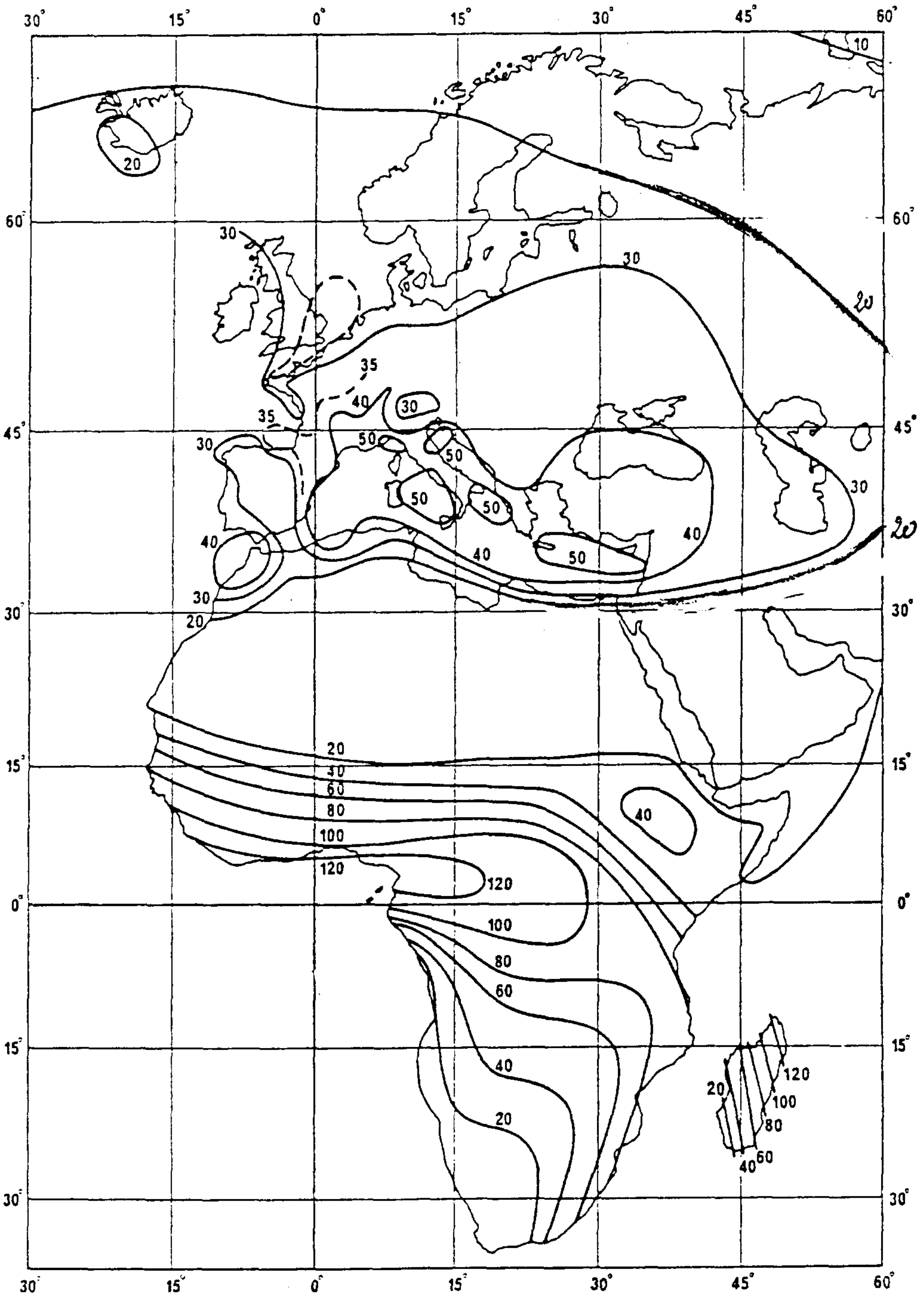


Figure C2 Rainfall contours for 0.01% of the time (Europe and Africa)

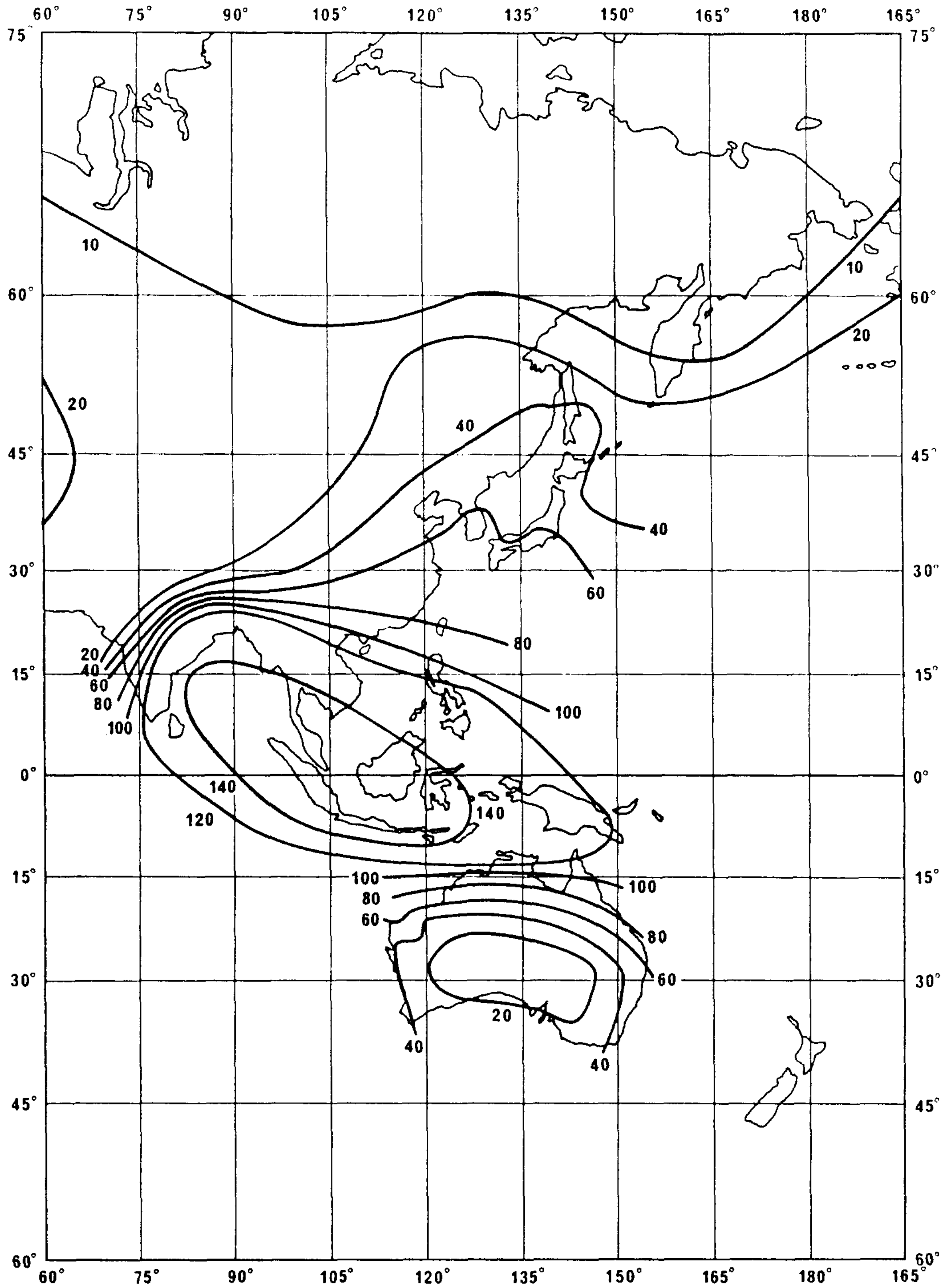


Figure C3 Rainfall contours for 0.01% of the time (Far East)

Appendix D

Maps for ΔN and β_0 (ITU-R rec. 452-5 [50])

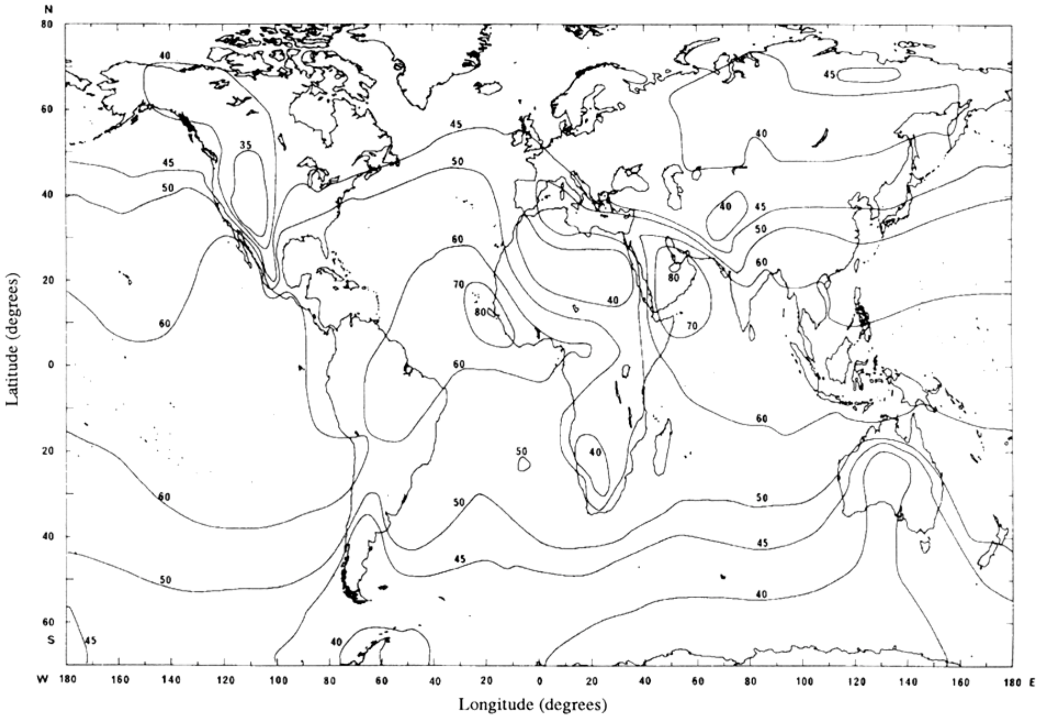


Figure D1 Average annual values of ΔN

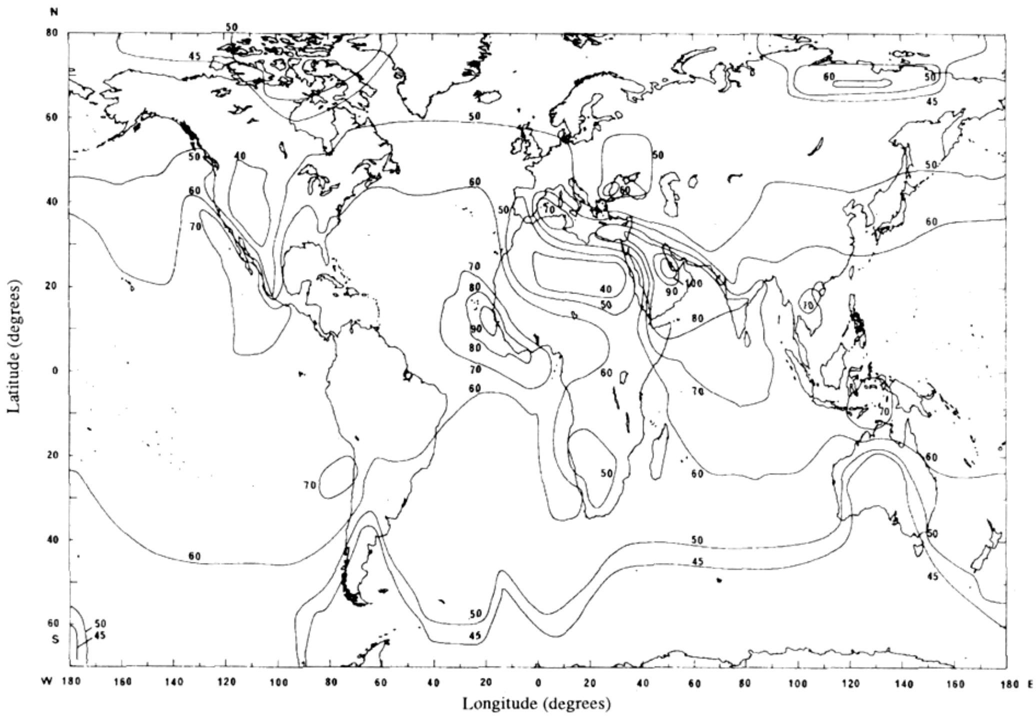


Figure D2 Maximum monthly mean values of ΔN
(for worst month prediction)

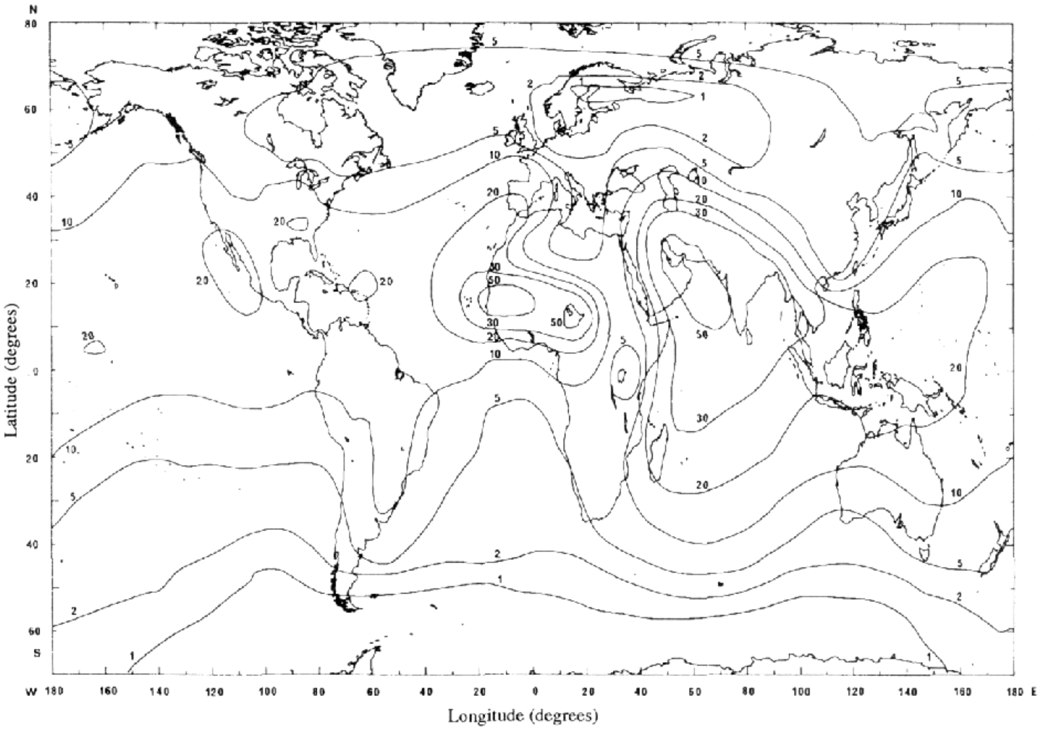


Figure D3 Average annual values of β_0

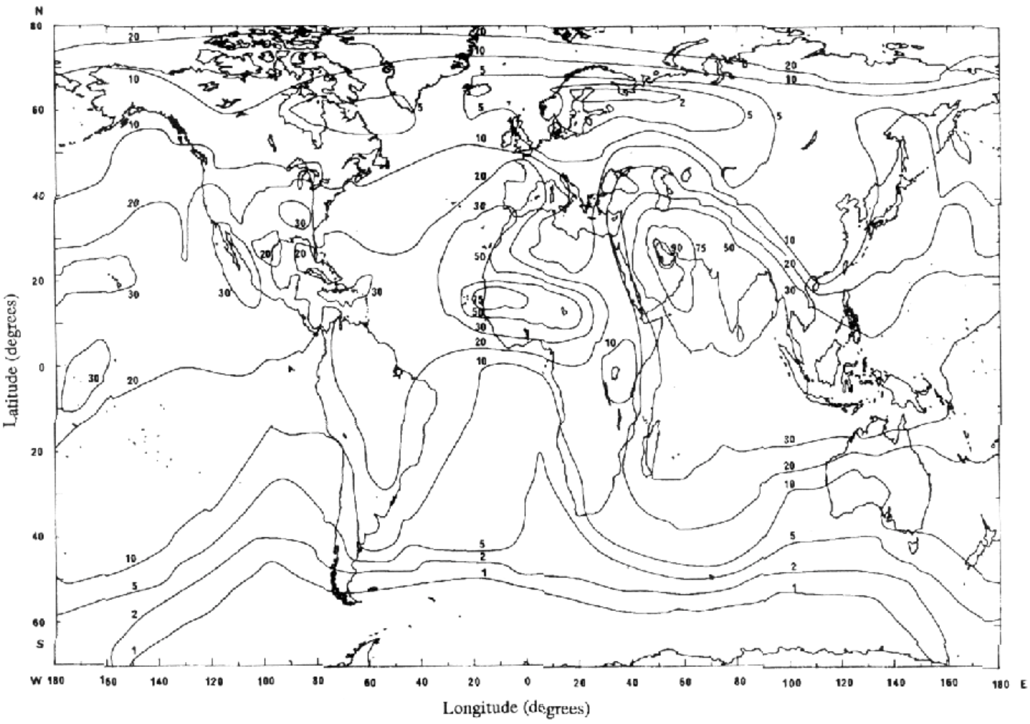


Figure D4 Maximum monthly mean values of β_0
(for worst month prediction)

Appendix E

List of abbreviations

Symbol	Unit	Signification
a	-	climatic factor
a	km	radius of earth
A	%	Availability
A	m^2	Aperture area
A	dB	Attenuation
A_{fs}	dB	free space loss
ATDE	-	Adaptive Time Domain Equaliser
ATPC	-	Automatic Transmit Power Control
α	degrees	angle
b	-	terrain factor
B	dB	notch/signature depth
BBE	-	Background Block Error
BBER	%	Background Block Error Ratio
BER	-	Bit Error Ratio
c	m/s	speed of light in vacuum
C	dB	geographic coefficient
C/I	dB	Carrier-to-Interference ratio
CPA	dB	Co-Polarised Attenuation
C_R	dB	receiver constant
d	km	path length
D	m	diameter
Dem	-	Demodulator
DM	-	Degraded Minute
DS	MHz	Duplex Separation
δ		separation
e	-	base of natural logarithm (e=2.7182818)
e	hPa	water vapour pressure
E	V/m	Electrical field strength
EB	-	Errored Block
EIRP	dBW	Effective Isotropic Radiated Power
E_p	mrad	path inclination
ES	-	Errored Second
f	GHz	radio frequency
F	dB	Fade margin
F	dB	noise figure

Symbol	Unit	Signification
F/B	dB	front-to-back ratio
F_1	m	first Fresnel zone
FDM	-	Frequency Division Multiplex
FM	-	Frequency Modulation
G	dB	antenna gain
GPS	-	Global Positioning System
Γ	MHz	radio channel spacing
γ	dB/km	specific attenuation
h	m	altitude
H	%	relative humidity
H	-	Horizontal polarization
HRDL	-	Hypothetical Reference Digital Link
HRDP	-	Hypothetical Reference Digital Path
HRDS	-	Hypothetical Reference Digital Section
HRX	-	Hypothetical Reference Connection
η		aperture efficiency
η	-	fading activity factor
I	-	Improvement factor
IG	-	International Gateway
ISDN	-	Integrated Services Digital Network
ITU	-	International Telecommunications Union
k	-	k-value for ray bending
K	-	geoclimatic factor
k	J/K	Boltzmann's constant
L	dBm	signal level
LO	-	Local Oscillator
LOS	-	Line of Sight
λ	-	failure rate
λ	m	wavelength
M	-	modified radio refractivity
Mod	-	Modulator
MTBF	-	Mean Time Between Failures
MTTR	-	Mean Time To Repair
n	-	index of refraction
N	-	radio refractivity
N	%	Unavailability
NFD	dB	Net Filter Discrimination
ν	m	pitch distance
p	hPa	air pressure
P	W/dBm	power
p	W/m^2	power density

Symbol	Unit	Signification
P	%	probability
P_0	%	fading occurrence factor
PDH	-	Plesiochronous Digital Hierarchy
PEP	-	Path End Point
P_L	%	percentage of time gradient ≤-100 (N/km)
π	-	pi = 3.141593
θ	degrees	angle
r	m	radius
R	mm/h	rain rate/intensity
RBER	-	Residual Bit Error Ratio
Rx	-	Receiver
ρ	g/cm^3	water content
S	m	standard deviation of terrain elevations
S	m	vertical antenna separation
S/I	dB	Signal-to-Interference ratio
SDH	-	Synchronous Digital Hierarchy
SES	-	Severely Errored Second
SESR	%	Severely Errored Second Ratio
sf	/MHz	signature factor
STM	-	Synchronous Transfer Mode
SWR	-	Standing Wave Ratio
T	Kelvin	absolute temperature
t	Celsius	temperature
TDM	-	Time Division Multiplex
Tx	-	Transmitter
τ	ns	time delay
v	m/s	velocity
V	-	Vertical polarization
VC	-	Virtual Container
VP	-	Virtual Path
VSWR	-	Voltage Standing Wave Ratio
W	MHz	Bandwidth
WARC	-	World Administrative Radio Conference
XPD	dB	Cross Polar Discrimination
XPI	dB	Cross Polar Interference
XPIC	-	Cross Polar Interference Canceller
XPIF	dB	Cross Polarization Improvement Factor
ψ	degrees	angle

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