

POINT-TO-POINT RADIO LINK ENGINEERING



A SELF-LEARNING E-BOOK BASED COURSE, BY RADIO ENGINEERING SERVICES

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STUDENT GUIDE

Introduction

Welcome to the Course on "Point-to-Point Radio Link Engineering".

The aim of this Course is to give you a practical guide, moving from basic notions in Radio Propagation at microwave frequencies and coming to applications in Radio Link Design.

The Course Notes cover the main topics in Radio Propagation and Point-to-Point radio link engineering. They apply to the design of Microwave Links in the frequency range from about 450 MHz up to 60 GHz.

With the "HERALD Lab", you can use the HERALD program (a software tool for radio link design) to perform a number of guided exercises and test the HERALD approach in implementing the design process.

As a whole, the Course has been designed with the objective of actively involving the reader in navigating through the text and in practicing with exercises. The most relevant aspect is that the HERALD Lab exercises, in addition to the Course notes, provide guidance to practical applications in the field of microwave link design.

We do not expect to offer a complete Radio Engineering manual, nor a tutorial on every aspects of Radio Propagation. All the topics are presented in an intuitive, practical style, not with a theoretical / academic approach.

It is assumed that the reader is somewhat familiar with basic notions in modulation techniques, radio equipment and systems, as well as in elementary electromagnetic physics.

Course Notes

The Course Notes are organized in eight sections. We recommend you proceed through the sections in published order to ensure complete understanding of the material. The first two sections are introductory:

Section 1 introduces the radio system and its structure

Section 2 introduces the basics of microwave link engineering

The next four sections are almost self contained and the final two cover propagation principles.

A moderate number of additional hypertext links have been included throughout the text. We recommend you return to the link and continue the section after following hypertext links to ensure you don't lose your place in this course.

The Course Notes are subdivided into a "Basic Techniques" (white background) and an "Advanced Techniques" (green background) course. Initially, you may skip the advanced techniques and return to them at a later reading.

Paragraphs giving only additional comments about some topics are indicated by a pink background.

Herald Lab

The HERALD Lab has been included in this Course with two objectives:

- as a complement of the Course Notes presentation, showing how the propagation concepts and engineering rules are applied in practical cases;
- as an introduction to HERALD functions and commands.

HERALD Lab will improve both your understanding of radio link engineering and your skills in using the HERALD program.

Each Session in the HERALD Lab starts with the "HERALD Functions" chapter. This chapter briefly explains how design rules, presented in the Course Notes, are implemented in the HERALD program. It does not substitute the HERALD Help, where you find a more detailed guide to the program use.

The HERALD Lab Session continues with exercises. Each exercise provides detailed instructions on program steps to execute a given task. Some exercises (in particular in the first sessions) may appear rather easy and even tedious. However, we suggest to skip them only if you already have a good practice in HERALD use.

Herald Demo version may be downloaded by registering at the following link:

<http://www.heraldpro.com>

Herald Demo provides all the features required to complete the Herald Lab exercise.

SECTION 1 – RADIO HOP CONFIGURATION

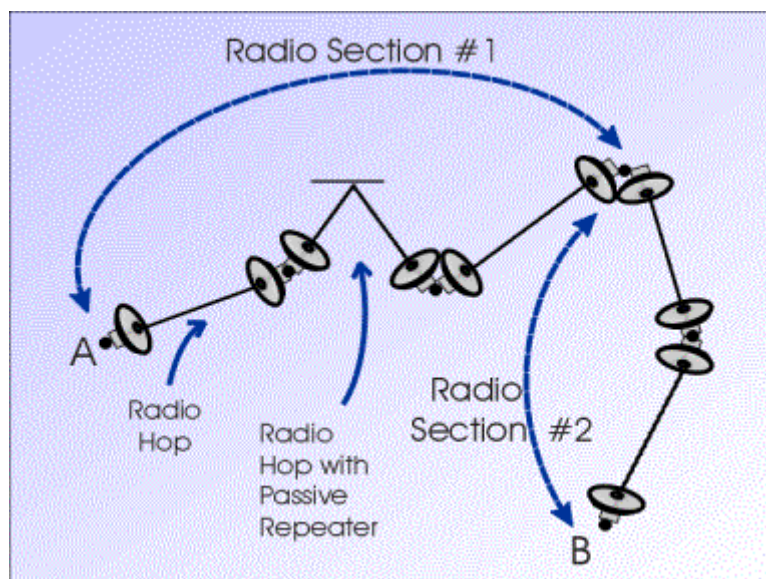
Summary

In this Session we introduce the basic configuration of a Point-to-Point Radio Link. The fundamental parameters useful to describe radio site installations are presented, including antenna, radio equipment and ancillary subsystems. Hops with passive repeaters are finally discussed.

Point-to-Point radio-relay links

A Point-to-Point radio-relay link enables communication between two fixed points, by means of radiowave transmission and reception. The link between two terminal radio sites may include a number of intermediate radio sites.

The direct connection between two (terminal or intermediate) radio sites is usually referred as a "Radio Hop". In some cases, a radio hop may include a passive repeater.



A multi-hop radio-relay link, connecting A to B, divided in two Radio Sections

A multi-hop radio-relay link can be divided in a number of "Radio Sections", each of them being made of one or more radio hops. Transmission performance is usually summarised on a radio section basis.

General criteria for radio network planning and design is not discussed here; just a very brief summary is given below. The overall process can be usually divided in two steps :

- 1) Preliminary network or link planning. A partial list of activities carried on at this stage is:
 - a) Consideration of Regulatory environment;
 - b) Identification of Terminal radio sites;
 - c) Service and Capacity requirements;
 - d) Performance objectives;
 - e) Frequency band selection;
 - f) Identification of suitable Radio equipment and Antennas;
 - g) Sample design of typical hops, estimate of maximum hop length.

- 2) Route and Intermediate Site Selection. A number of factors have influence on this choice; among others:
 - a) Maximum hop length;
 - b) Nature of Terrain and Environment;
 - c) Site-to-Site terrain profile; visibility and reflections
 - d) Angular offset from one hop and adjacent hops (to avoid critical interference);
 - e) Need for passive repeaters.
 - f) Availability of existing structures (buildings, towers);
 - g) New structures requirements;
 - h) Access roads (impact on installation and maintenance operations);
 - i) Availability of Electric Power sources;
 - j) Weather conditions (wind, temperature range, snow, ice, etc.);
 - k) Local restrictions from regulatory bodies (authorization for new buildings, air traffic, RF emission in populated areas, etc.);

When a tentative selection of intermediate sites is available, the final design goes through an iterative process :

- Hop configuration and detailed hop design;
- Prediction of Hop and Section performance;
- Identification of critical hops;

- Revision of Route and Site selection;
- Revision of Hop configuration and of detailed hop design.

In the following Sections we focus on this design process, going through site and hop configuration and leading to performance predictions. As a first topic, we discuss the parameters useful to describe the site and hop configuration.

Site and Hop parameters

A radio hop is described in terms of :

- 1) Topographical data and terrain description:
 - a) Radio site position: geographical coordinates or other mapping information; elevation above sea level (a.s.l.);
 - b) Path length and orientation (azimuth: note that in plane geometry the azimuths computed at the two extremes of a line segment differ by 180 deg, while this is not true in spherical geometry; so, two path azimuths, referred to each radio site, are usually indicated);
 - c) Path profile as derived from paper or digital maps: note that accuracy requirements are widely different throughout a radio path, since the elevation of possible obstructions should be accurately estimated, while significant profile portions (where no obstruction or reflection is expected) could be almost ignored.
- 2) Radio equipment, antennas and ancillary sub-systems installed at each radio site; in the following sections, the main parameters useful to describe the radio site installation will be discussed.
- 3) Specific aspects on equipment installation and operation:
 - a) Antenna positioning: installation height and pointing; space diversity option, antenna spacing;
 - b) Frequency used: (average) working frequency (usually referred in hop computations and link budget); detailed frequency plan (go and return RF channels at each radio site, required for interference analysis);
 - c) RF protection systems (use of 1+1 or n+1 frequency diversity, hot stand-by, etc.)

- d) Use of passive repeaters: flat reflector or back-to-back antenna system, repeater site parameters, reflector or antenna positioning and pointing.
- 4) Climatic and environmental parameters: they are usually required by propagation models (atmospheric refraction, rain, etc.), so they will be discussed while presenting such models.

Finally, let us consider several attenuation or degrading factors, such as:

- Atmospheric absorption loss;
- Obstruction loss;
- Any other systematic loss throughout the radio path (additional losses);
- Rx threshold degradation due to ground reflections;
- Rx threshold degradation due to interference.

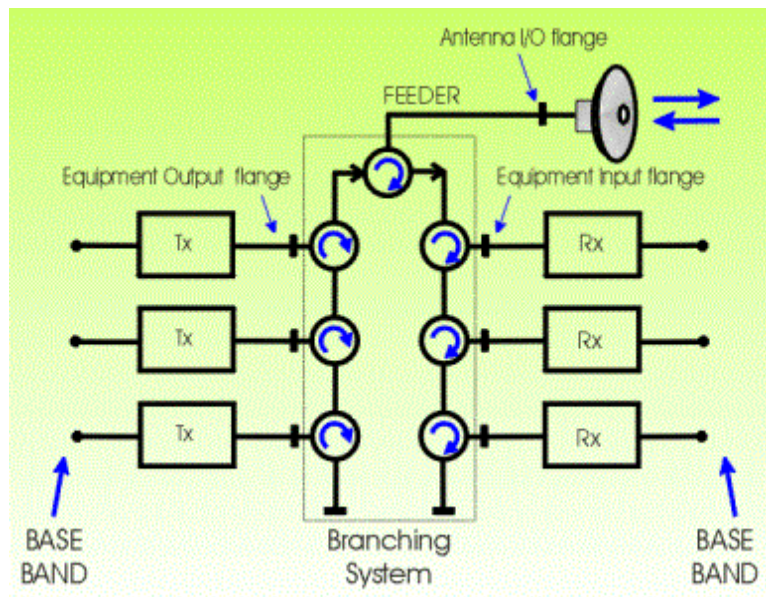
The above impairments will be discussed in the following sessions, where suitable models to estimate their impact on hop performance are considered.

However, it may happen that the inputs required to apply such models are not fully available or that other reasons suggest not to go through a specific analysis.

In that case, we can include among hop parameters also a rough estimate (or a worst case assumption) of losses or degradations caused by the impairments listed above.

Radio Equipment

A simplified block diagram of a sample radio site installation is shown below.



An example of radio equipment block diagram, in the case of multiple RF channel operation, using a single antenna for both transmission and reception.

Even if this example shows a specific configuration, it is useful as a reference in the following presentation. Other configurations of particular interest are:

- Single RF channel installations, where no branching system is needed;
- Outdoor installations, where radio equipment is directly connected to the antenna, without feeder line.

From the viewpoint of a single radio hop design, we can limit information about Radio Equipment to the very basic parameters:

- Range of operating frequencies;
- Transmitted power P_T ;
- Receiver threshold P_{RTH} (minimum received power required to guarantee a given performance level);

Note that:

- 1) Both the transmitted power and the receiver threshold are usually referred at the equipment input / output flanges, not including branching filter losses.
- 2) When the transmitter is equipped with an Automatic Transmitted Power Control (ATPC) device, the Tx power to be considered in hop design is the maximum power level (which should be applied every time the received signal quality is deeply affected by propagation impairments);

- 3) The receiver threshold is the minimum received power required to achieve a given performance level; in digital systems, the reference performance is usually set

at Bit Error Rate (BER) = 10^{-3} , while other reference levels may be adopted if needed.

Performance objectives in digital radio links will be discussed in the final Session of this course.

Additional parameters can be useful for a more complete understating of the equipment operation, even if they are not directly involved in the hop design:

- Equipment user capacity; for digital systems, bit-per-second or number of standardized signals, like STM-1 or DS1 signals; for analog systems, number of telephone or television channels;
- Bit rate (R) of the modulated (emitted) signal (this may differ from the user capacity, mentioned above, since the transmission equipment may include additional bits for service and monitoring channels, channel coding, etc.);
- Modulation technique;
- Symbol rate of the modulated (emitted) signal; in analog systems, an equivalent parameter is the baseband (modulating) signal bandwidth;
- Emitted spectrum and modulated signal bandwidth.

The Symbol rate S_R depends on the emitted signal bit rate R and on the modulation technique :

$$S_R = R / L$$

where L is the number of bits coded in a single modulated waveform (L = 2 in QPSK modulation, L = 6 in 64QAM modulation).

For advanced tasks in Radio Hop design, more detailed data on radio equipment are required. This includes :Rx noise bandwidth B_N and Rx noise figure NF;

- Signal-to-Noise (S/N) ratio at the Rx threshold;
- Co-channel Carrier-to-Interference ratio at receiver input, producing the threshold BER, in the absence of thermal noise (high Rx level);
- Typical spacing between adjacent RF channel;
- Net Filter Discrimination (NFD) at the above spacing;
- Results of signature measurement;
- Possible use of Automatic Transmitted Power Control (ATPC) and related parameters;

- Possible use of Cross-Polar Interference Canceller (XPIC) and related parameters.

The Signal-to-Noise (S/N) ratio can be expressed in terms of received power P_R , receiver noise bandwidth B_N , and receiver noise figure NF :

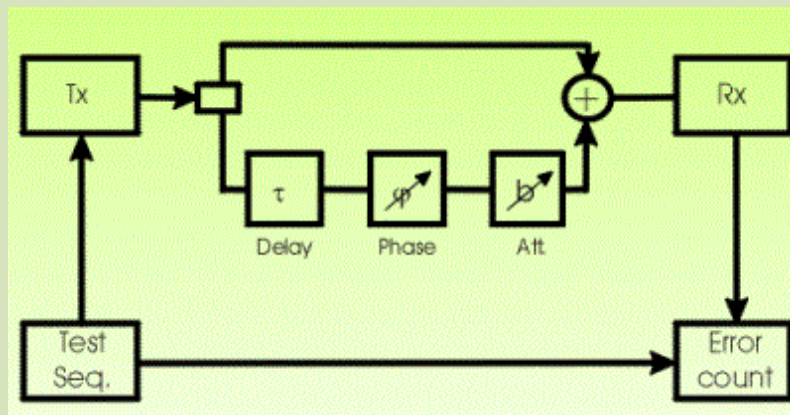
$$(S/N)_{dB} = P_R - [(NF)_{dB} - 114 + 10 \log_{10}(B_N)]$$

where P_R is expressed in dBm and B_N in MHz; the expression in square brackets gives the receiver thermal noise power.

Advanced - Digital Equipment Signature

The equipment signature gives a measure of the sensitivity of radio systems to channel (amplitude and group delay) distortions as produced during multipath propagation events. More specifically, it is used for digital radio systems with signal bandwidth larger than about 10-12 MHz (on this type of signals, significant frequency selective distortion is not produced if the bandwidth is narrower; other signals may be sensitive to frequency selective multipath even with a narrower bandwidth).

Measurement Set-up - The Tx signal is modulated by a test sequence and is transmitted through a simulated multipath channel, modeled as a two-path channel (direct plus echo branches).



Signature measurement setup.

As shown in the above figure, the power level and the phase of the delayed signal can be adjusted by means of a variable attenuator and a variable phase shifter.

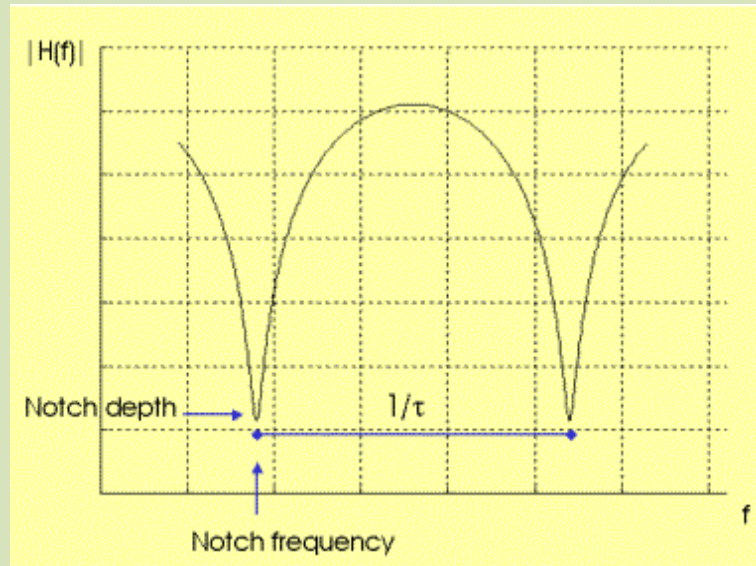
Assuming a normalized signal amplitude equal to 1 in the direct branch and b (< 1) in the delayed branch, then the Two-Path Channel Transfer Function is:

$$H(f) = 1 - b \cdot \exp[-j(2\pi f\tau - \varphi)] = 1 - b \cdot \exp[-j2\pi\tau(f - f_0)]$$

τ = Echo delay, assumed as constant (= 6.3 ns in the original Bell Labs / Rummler model);

$f_o = \phi / 2\pi\tau$ = Notch Frequency (corresponding to the minimum amplitude of the transfer function);

B = Notch depth (in dB) = $-20 \log_{10} (1 - b)$.



Two-path channel transfer function, with definition of Notch Frequency and Notch Depth.

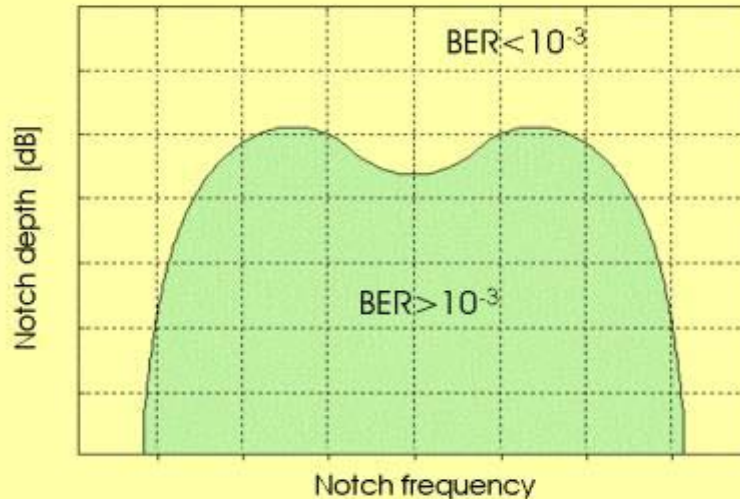
The above definition refers to a Minimum-Phase Transfer Function. Otherwise, if the signal amplitude is b (< 1) in the direct branch and 1 in the delayed branch, then similar definitions apply, but a Non-Minimum-Phase Transfer Function is obtained.

Measurement Procedure - As shown by the above definitions, the notch frequency is controlled by varying the echo phase ϕ ; while the notch depth depends on the echo amplitude b .

The first step in the measurement procedure is to select a given Notch Frequency f_o , with echo amplitude close to zero. Then, the echo amplitude is increased, making the transmission channel more and more distorting. Consequently, the Bit Error Rate (BER) will increase.

The notch is made deeper, up to the "Critical Depth B_c ", when $BER = 10^{-3}$ (or any other desired threshold). The point $[B_c, f_o]$ is a signature point.

The same steps are repeated for different notch frequencies, in order to plot a complete signature curve in the Notch Depth vs. Notch Frequency plane.



Equipment Signature in the Notch Depth / Notch Frequency plane.

In that plane each point corresponds to a pair of notch parameters, so it is representative of a particular channel state. The points below the signature show the channel states for which $BER > \text{Threshold}$. Therefore, the area below the signature gives a measure of the receiver sensitivity to multipath distortions. For an unequalized signal, typical signature width may be of the order of 1.5 times the symbol rate, while using equalization it is halved at least.

To predict multipath outage, it is often required that the equipment signature be defined by only two parameters (signature width and depth). In most cases the shape of actual equipment signatures allow for a "square brick" approximation.

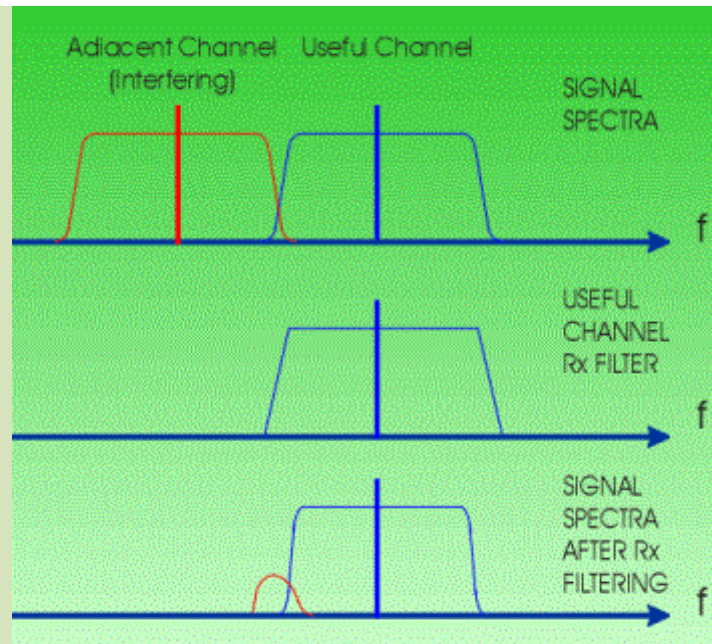
Equipment parameters used in Interference analysis

Net Filter Discrimination (NFD) - It is used to characterize the radio system ability to limit the interference coming from an adjacent radio channel.

NFD gives the improvement in the Signal-to-Interference ratio passing through the Rx selectivity chain (RF, Intermediate, baseband stages) :

$$NFD = \frac{[S/I]_{DEC}}{[C/I]_{RF}}$$

where $(C/I)_{RF}$ is defined at the RF input stage and $(S/I)_{DEC}$ at the decision circuit stage.



Signal spectra at the receiver input and output and Rx selectivity.

As shown by the figure above, the NFD depends on :

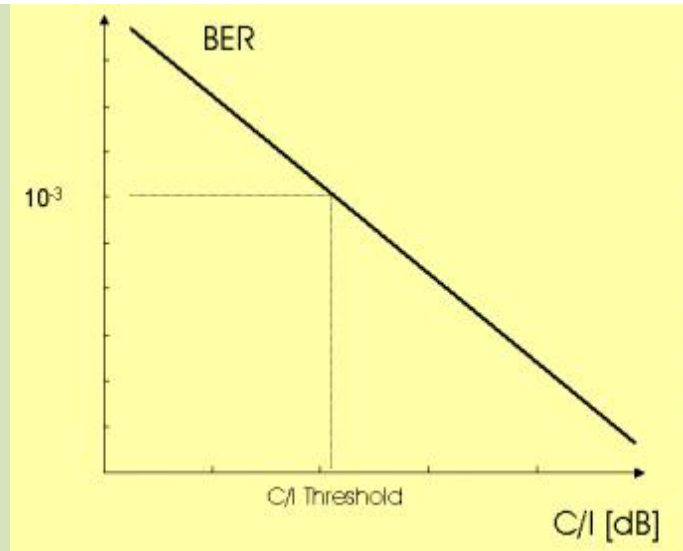
- Interfering signal spectrum (Tx filtering);
- Channel spacing;
- Overall Rx selectivity in the Useful Channel.

The NFD can be measured or evaluated for interference between identical signals (adjacent channel interference in a homogeneous channel arrangement) and also when the interfering signal is different (in capacity and/or modulation format) from the useful one (interference in a mixed signal network).

So, for any pair of useful and interfering signals and for each value of the channel spacing, a NFD value can be evaluated.

Threshold Carrier-to-Interference ratio - In some applications the received signal may be interfered by a co-channel signal, with identical capacity and modulation format (for example in co-channel frequency arrangements, with use of both orthogonal polarizations).

The receiver sensitivity to co-channel interference is estimated by a Bit Error Rate (BER) vs. C/I curve, as shown in the figure below.



Bit Error Rate (BER) vs. Carrier-to-Interference ratio (C/I), with indication of C/I threshold for $BER = 10^{-3}$.

The measurement is made in absence of any significant thermal noise contribution (high Rx power level).

From this measurement, it is possible to know the Carrier-to-Interference ratio corresponding to the threshold error rate (for example $BER = 10^{-3}$).

Cross-Polar Interference Canceller (XPIC) Gain - The Interference Canceller is used to reduce the interference coming from a signal transmitted on the same frequency with orthogonal polarizations (usually the useful and interfering signals have identical capacity and modulation format).

We assume that the signal-to-interference ratio at the receiver RF input is $(C/I)_{RF}$.

The interference canceller works in such a way that the signal-to-interference ratio appears to be improved to a higher value $(C/I)_{APP}$ defined as

$$[C/I]_{APP} = [C/I]_{RF} \cdot XPIC_{Gain}$$

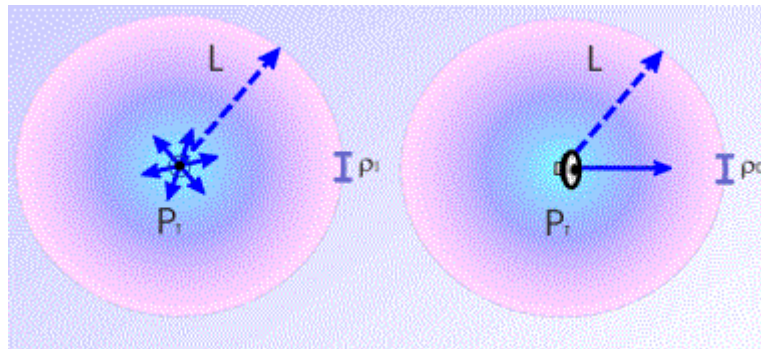
where $XPIC_{Gain}$ is defined as the gain produced by the cross-polar canceller. The interference impairment is computed by assuming $(C/I)_{APP}$ to be the actual signal-to-interference ratio.

Antennas

Gain definition and related parameters

Let us consider a radio transmitter with power P_T coupled to an Isotropic Antenna (an ideal source of EM Radiation, that radiates uniformly in all directions). At the distance L from the antenna, the emitted power will be uniformly distributed on the surface area of a sphere of radius L , so that the Power Density ρ_I is :

$$\rho_I = \frac{P_T}{4\pi \cdot L^2}$$



EM power emission from an Isotropic Antenna (left) and from a Directive Antenna (right)

Then we substitute the Isotropic Antenna with a Directive Antenna, while the transmitted power is again P_T . We imagine to measure the Power Density where the antenna axis intercepts the sphere surface, with result ρ_D

The antenna gain gives a measure of how much the emitted power is focused in the measurement direction, compared with the isotropic case. As a result of the "experiment" described above, the antenna gain is defined as :

$$g = \frac{\rho_D}{\rho_I}$$

This definition leads to $g = 1$ for the isotropic antenna.

Generally speaking, the antenna gain is related to the ratio between antenna dimension and the wavelength λ . More specifically, in the case of reflector antennas, the antenna gain g is given by :

$$g = \eta \cdot \left(\frac{\pi \cdot D}{\lambda} \right)^2 = \eta \cdot \frac{4\pi \cdot A}{\lambda^2} = \frac{4\pi \cdot A_E}{\lambda^2}$$

where D is the reflector diameter, η is called "antenna efficiency" (typically in the range 0.55 - 0.65), A is the reflector area and $A_E = \eta \cdot A$ is the Antenna Effective Area.(or Aperture).

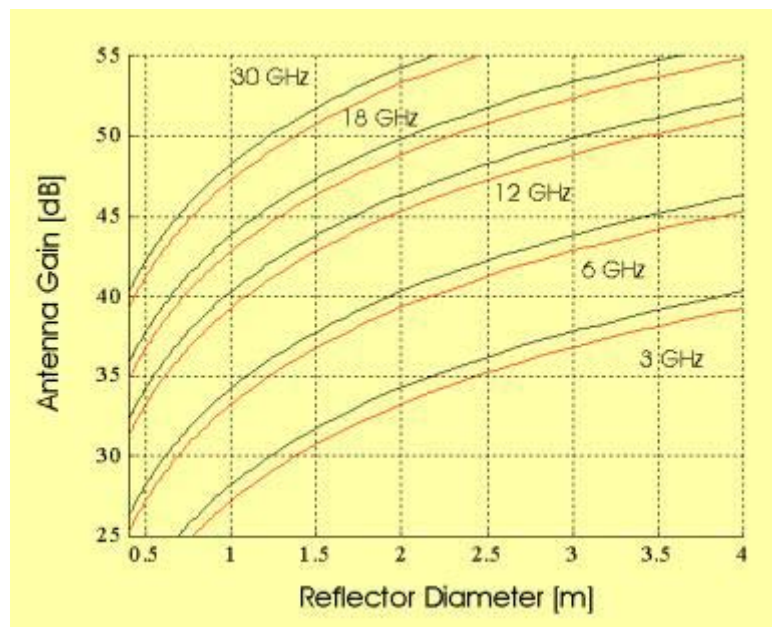
In logarithmic (decibel) units :

$$G(\text{dB}) = 10 \text{Log}_{10}(g) \approx 20 \text{Log}_{10}(D) + 20 \text{Log}_{10}(F) + 18.2 \pm 0.5$$

where the ± 0.5 dB term depends again on antenna efficiency; it is assumed to express the diameter D in meters [m] and the frequency F in GigaHertz [GHz].

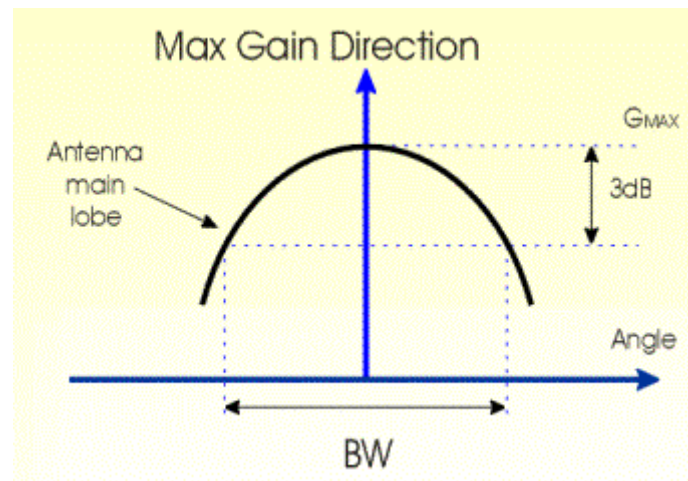
Note that, for given dimension, the antenna gain increases with frequency (6 dB higher if the frequency is doubled). Similarly, at a given frequency, the gain increases 6 dB if the antenna diameter is doubled.

Below, some examples of antenna gain vs. diameter and frequency are given.



Antenna gain vs. diameter and frequency; the double (red, black) line gives a range of possible gains, depending on antenna efficiency.

The 3-dB beamwidth BW (see graphical definition below) is related to antenna gain; as the gain increases, the EM energy is focused in a narrower beam.



Definition of the antenna 3-dB Beamwidth BW.

For reflector antennas, some simple "rules of thumb" are useful in relating antenna diameter D [m], working frequency F [GHz], gain G [dB], and the 3-dB beamwidth BW [deg] :

$$BW \approx \frac{22}{(F \cdot D)}$$

$$G \approx 45.5 - 20 \log_{10}(BW)$$

Note that these are approximate relations, fitting with "real" values within some margin; in particular cases this margin may be even large.

An additional concept in antenna operation is the Far Field Region. It is the region sufficiently distant from the antenna, where the electromagnetic (EM) field can be well approximated as a plane wave and the antenna diagram is stabilized. Closer to the antenna, the Near Field Region and the Fresnel (transition) Region are defined, where the antenna radiation diagram is not easily predicted. The boundary between the Fresnel and the Far Field Region is approximately at the distance :

$$d_{FF} = \frac{2 \cdot D^2}{\lambda}$$

Antenna Parameters for hop design

Point-to-point radio hops usually make use of high-gain directive antennas, which offer several advantages:

- both Transmission and Reception : the antenna gain is maximized in the desired direction.
- Transmission : the emitted radio energy is focused toward the receiver, thus reducing the emission of interfering radio energy in other directions;

- Reception : the receiver sensitivity to interfering signals coming from other directions is reduced.

However, in special cases, also antennas with sectorial or even omnidirectional coverage may be used (this is true mainly for point-to-multipoint applications).

In most cases, directive antennas are parabolic antennas or other reflector antennas (like Horn or Cassegrain antennas). The directivity patterns can be measured both in the vertical (elevation) and in the horizontal (azimuth) planes; however, we can often adopt the simplifying assumption that one diagram is applicable both to the vertical and to the horizontal planes. In that case, also the 3-dB antenna beamwidth is assumed to be the same in the two planes.

As far as interference problems are not considered in a single radio hop design, we can limit information about the antennas to the very basic parameters:

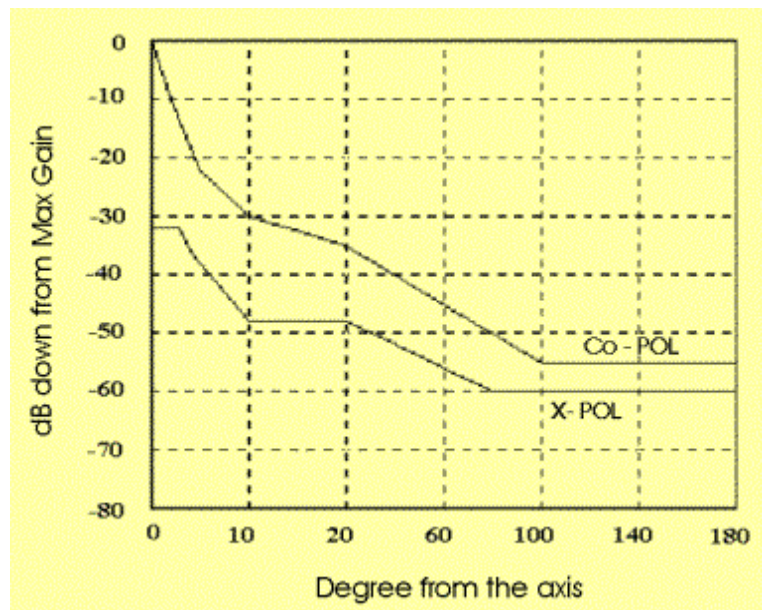
- Range of operating frequencies;
- Single or Double Polarization operation;
- Antenna gain;
- 3dB beamwidth in the vertical plane (this may be useful to analyze reflection paths).

An example of the antenna connection to radio equipment is given in the [Block diagram](#) shown above. Note that the antenna gain (as well as other antenna parameters) is referred to the antenna I/O flange.

Additional parameters can be useful for a more complete description of antenna operation:

- Antenna type (Parabolic, Horn, Cassegrain, etc.);
- Coverage type (omnidirectional, sectorial, directive);
- 3dB beamwidth in the horizontal plane (for sectorial antennas);
- Diameter (or more generally, physical dimensions);
- Voltage standing wave ratio (VSWR);
- Weight.

Moreover, the antenna diagram, as mentioned above, illustrates the antenna operation in directions other than the pointing (max gain) direction.

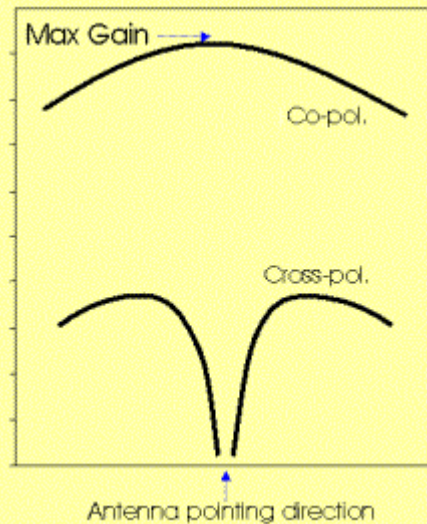


Antenna radiation diagram (mask) for Co-polar e X-polar operation (a different horizontal scale is used in the 0 - 20 deg range and in the 20 - 180 deg range).

Advanced - More on the Antenna radiation diagram

Some additional comments on antenna diagrams:

- The result of the antenna directivity measurement usually exhibits multiple lobes and nulls. A sidelobe envelope is estimated, giving a "mask diagram", useful to characterize the antenna directivity. In interference analysis the need arises to estimate the antenna gain in any direction and the antenna mask gives a conservative result.
- The pattern of co-pol and cross-pol antenna diagrams, close to the pointing direction, are significantly different, as shown in the figure below. While the co-pol pattern is rather flat, in the range of some tens of degree around pointing direction (maximum gain), the cross-pol pattern has a very narrow minimum in the same direction. In some cases it is convenient to point the antenna by searching for the minimum cross-pol signal level, instead of searching for the maximum co-pol signal. By this way, it is assured that, not only the maximum gain, but also the maximum cross-pol discrimination are obtained.



Example of Co-pol. and Cross-Pol. antenna diagrams, close to the antenna pointing direction

- The antenna directivity diagram is usually measured in a controlled environment, in order to characterize the "true" antenna response, without influence or errors produced by any external element.

In actual operation, the antenna response may be significantly altered by the surrounding environment. For example, an obstacle close to the main antenna lobe may produce a signal reflection, about 180° from the antenna pointing direction. This apparently reduces the antenna front-to-back decoupling, both in the co-pol and cross-pol diagrams.

The correct antenna positioning is a key factor in order to get antenna performance in real operating conditions as close as possible to measured parameters.

Ancillary equipment

A number of additional equipment and subsystems are working in a radio site. In the present context, we consider only what is strictly related to the design of a radio hop (so, we do not discuss power lines and back-ups, air conditioning, grounding, and other subsystems, even if they are of significant importance in the overall site operation).

Branching system

As shown in the [block diagram](#) above, a branching filter is required in radio transceivers for multiple RF channel operation.

In transmission, the function of the branching system is to multiplex RF channels on a single wide-band RF signal, suitable to be transmitted on a single antenna. Similarly, in reception, the branching system splits the multi-channel signal coming from the antenna into multiple RF channels, each addressed to the corresponding receiver.

The branching loss is different for the various RF channels (in Tx and Rx), depending on the number of filter ports and circulators to be passed through by the signal. However, in hop design, it is advisable to take account of highest loss, resulting from Tx and Rx branching.

In a branching configuration with a common Tx/Rx antenna (see [block diagram](#)), the branching loss include the loss of the circulator used to separate the Tx and the Rx branches.

Tx / Rx Attenuators

Power attenuators may be added in the transmitter or in the receiver chain, mainly to avoid an excessive power level at the receiver input (which may saturate the Rx front-end stage) and/or to avoid unnecessary power emission in short hops (interference reduction).

Note that many radio equipments now include power setting options or ATPC (Automatic Transmitted Power Control) devices, so that in most cases the use of external attenuators is no longer required.

In the context of radio hop design, the only parameter to be associated with Tx and Rx attenuators is the attenuation level itself.

Feeder Line

A feeder line is required to connect the antenna I/O flange to the radio equipment I/O port (or to the branching system I/O port). The exception is the outdoor configuration, with direct equipment-to-antenna connection.

The basic feeder parameters for radio link design are:

- Range of operating frequencies;
- Specific loss (expressed in dB per unit length).

Additional parameters, giving more details on feeder description:

- Feeder type (cable, rectangular waveguide, etc.);
- Weight (expressed in kg per unit length).

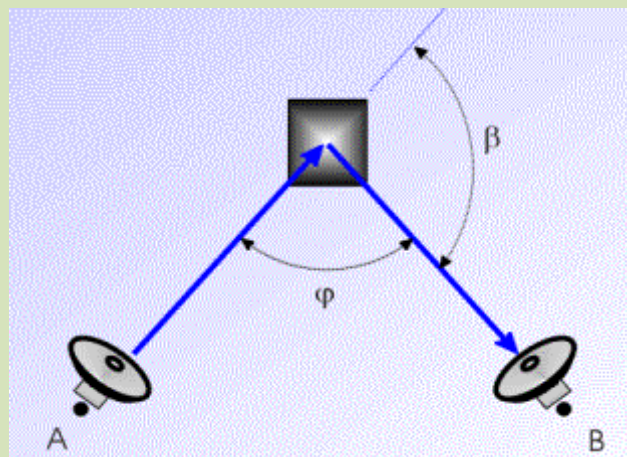
Advanced - Hops with a Passive Repeater

Passive Repeaters are used mainly in hops over irregular terrain, to by-pass an obstruction along the path profile.

Three Passive Repeater configurations are described below, while the corresponding Link Budget equations are presented in the next Session.

Single plane reflector - it is implemented as a metal surface, which is close to a 100% reflection efficiency. The surface flatness must be more and more accurate for increasing frequency (smaller signal wavelength).

The reflector works to deviate the incoming signal direction by an angle β . The geometry is shown in the figure below



Passive repeater implemented as a single plane reflector

Each path from a radio site to the repeater is called a "leg". So a radio hop with a single reflector is made of two legs.

Note that the useful or "effective" area A_E of the plane reflector is given by :

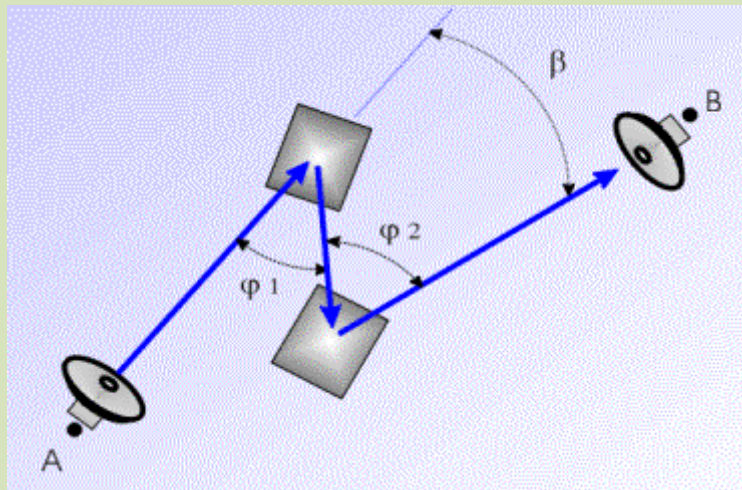
$$A_E = A_{REAL} \cdot \cos(\varphi / 2)$$

where A_{REAL} is the real reflector area and φ is the angle between the two rays.

It is estimated that for $\varphi > 120^\circ$ (corresponding to $\beta < 60^\circ$) the effective area is so reduced that it is not practical the use of a single reflector, since very large panels should be installed.

Double plane reflector - It is used when the change in signal direction (β) is lower than 60° or when it is not possible to find a suitable position for a single reflector, where visibility with both hop terminals is assured.

Usually, the two reflectors are arranged fairly close together. A typical double reflector geometry is shown below.



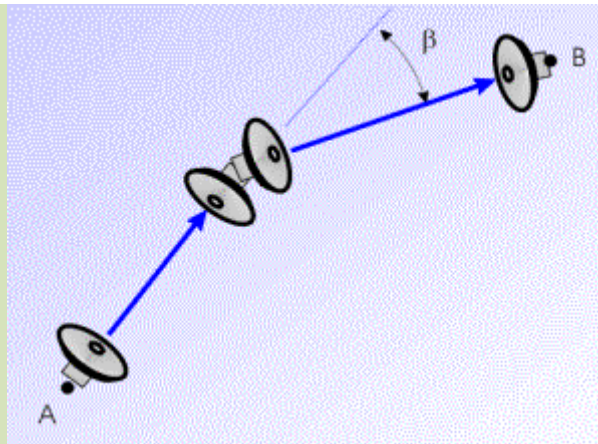
Passive repeater implemented as a double plane reflector

A radio hop with a double reflector is made of three legs.

With a double reflector arrangement it is possible to operate even if the angle β is close to 0° .

The reflector effective area is given by the same formula used for the single reflector, so that the angle between the two rays, at both reflectors, should be as low as possible.

Back-to-Back antenna configuration - Another passive repeater arrangement can be obtained by using two antennas with a short feeder (cable, waveguide) connection.



Passive repeater implemented as a two-antenna back-to-back arrangement

From a geometrical point of view, the back-to-back antenna system has a wider and more flexible application field, compared with a single reflector system. From a given repeater position, any change in signal direction (β) can be obtained.

However, single or double reflectors may be implemented, if needed, with surfaces much wider than the usual antenna size. Moreover, the reflector efficiency is close to 100%, compared to some 55% antenna efficiency.

So, when the power budget is limited, the back-to-back antenna system may be a poor solution.

This concludes Section 1 of the PPRLE. Please proceed to Herald Lab Exercise 1.

End of Section #1

SECTION 2 – BASICS IN LINK ENGINEERING

Summary

In this Session the Free Space radio link equation is presented, together with the concept of Free Space Loss. Then, terrestrial radio hops are considered and a brief summary is given of the most significant propagation impairments. We discuss the Link Budget, in order to estimate the Fade Margin, and how to use the Fade Margin in predicting the outage probability. Finally, the radio link equation is revised to include the use of passive repeaters.

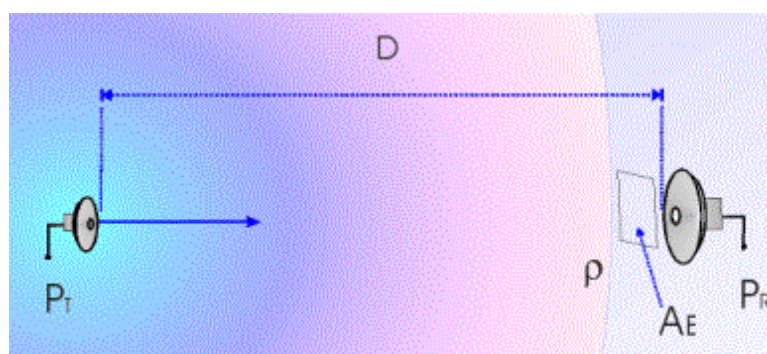
Free Space propagation

We approach radio link engineering by first considering an ideal propagation environment, where transmission of radio waves from Tx antenna to Rx antenna is free of all objects that might interact in any way with electromagnetic (EM) energy. This assumption is usually referred as "Free Space" propagation.

Let us consider a radio transmitter with power p_T coupled to a directive antenna with maximum gain on the axis g_T .

At distance D from the transmitting antenna (sufficiently large, in order that Far Field conditions are satisfied), the Power Density on the antenna axis is :

$$\rho = \frac{P_T \cdot g_T}{4\pi \cdot D^2}$$



Computation of Received Power in Free Space propagation

Now we imagine that, at the distance D , a receiving antenna is installed. The antenna "effective aperture" or "effective area" A_E gives a measure of the antenna ability to capture a fraction of the radio energy distributed at the receiver location. Assuming no receiver mismatch, the power p_R , at the receiver antenna output flange, is :

$$P_R = \rho \cdot A_E = \frac{P_T \cdot g_T \cdot A_E}{4\pi \cdot D^2}$$

Taking account that the relation between the Rx antenna gain and the antenna "effective aperture" is :

$$g_R = \frac{4\pi \cdot A_E}{\lambda^2} \quad A_E = \frac{g_R \cdot \lambda^2}{4\pi} = \frac{g_R}{4\pi} \cdot \left(\frac{c}{F}\right)^2$$

the received power equation becomes :

$$P_R = P_T \cdot g_T \cdot g_R \cdot \left(\frac{c}{4\pi \cdot D \cdot F}\right)^2$$

where F is the frequency of the transmitted signal, λ is the wavelength, and $c = \lambda F$ is the propagation speed, which can be assumed to be about $3 \cdot 10^8$ m/s, with good approximation, both in the vacuum and in the atmosphere.

This is usually known as the "Free Space Radio Link Equation." Using logarithmic units, it can be written as :

$$P_R = P_T + G_T + G_R - 92.44 - 20 \cdot \text{Log}_{10}(F) - 20 \cdot \text{Log}_{10}(D)$$

where upper-case letters are used to express power in dBm and gains in dB, while the same letters in lower-case had been previously used for non-logarithmic units.

Note that frequency must be expressed in GHz and distance in km, otherwise the 92.44 constant is to be modified accordingly (e.g. : with distance in miles, the constant is 96.57; with frequency in MHz, the constant is 32.44).

The above equation can be also written as :

$$P_R = P_T + G_T + G_R - FSL$$

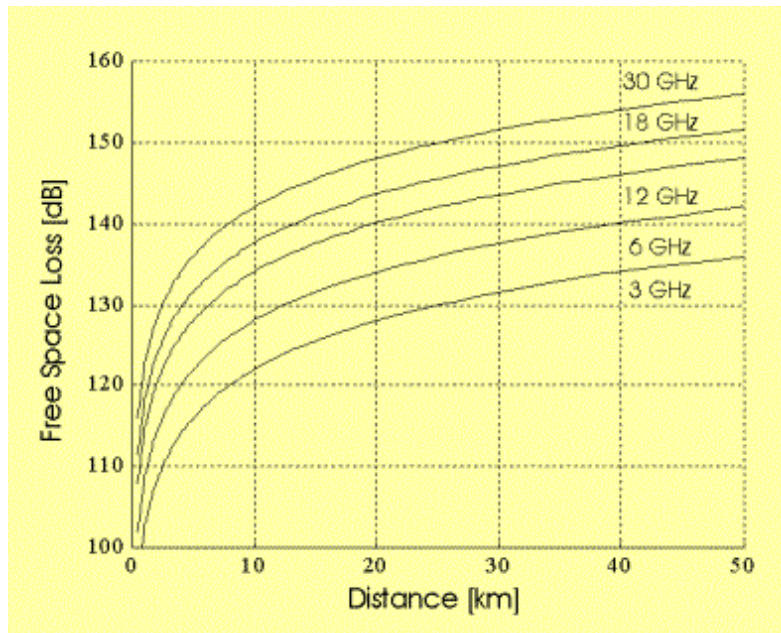
where FSL is called Free Space Loss, given by:

$$FSL = 92.44 + 20 \cdot \text{Log}_{10}(F) + 20 \cdot \text{Log}_{10}(D)$$

If we assume to use Isotropic Antennas ($G = 0$ dB) both at the transmitting and at the receiving site, then :

$$P_R = P_T - FSL$$

so FSL is also defined as "loss between isotropic antennas".



Free Space Loss vs. distance and frequency

Comments on Free Space Loss

The concept of Free Space Loss, and the related formulas, need some comments. First, the term "loss" could suggest some similarity with losses in coaxial cables or other guided transmission of electromagnetic (EM) energy, where we observe an interaction and power transfer from the EM wave to the propagation medium. Here, we are talking about "Free Space Propagation": the propagation medium is the vacuum and no interaction exists. The Free Space Loss is just to be referred to the density of EM energy, which follows the inverse square-law dependence versus distance from the source.

A second problem is the role of frequency in the Free Space Loss formula. Is the Free Space a transmission medium more lossy as frequency increases? Let us consider the two equivalent forms of the radio link equation given above :

$$P_R = P_T \cdot G_T \cdot A_E \cdot \frac{1}{4\pi \cdot D^2} = P_T \cdot G_T \cdot G_R \cdot \left(\frac{c}{4\pi \cdot D \cdot F} \right)^2$$

The first expression is probably more intuitive and should be preferred when we try to understand the physical concept underlying free space propagation. The Tx antenna is described by its gain (the ability to focus the EM power toward a given direction), while the Rx antenna is described by its equivalent aperture (the ability to capture the EM power distributed at the receiver location).

On the other hand, we passed to the second expression, where both the Tx and Rx antenna gains appear, since it looks attractive for its symmetric form. The frequency dependence in this case is due to the decreasing effective aperture of the receiving antenna (for a given gain), as the frequency increases. It is just a formal artifice to include frequency dependence in the so-called Free Space Loss.

As a conclusion, the Free Space Loss is a convenient step in evaluating the received power in a radio link and it is useful in order to put formulas in a manageable form. However, care should be paid about the physical concept related to it, in order to avoid misleading interpretations.

Terrestrial radio links

We now depart from the Free Space assumption and we put again our feet to the earth. We consider radiowave propagation between two terrestrial radio sites, in the context of radio hop design.

Transmitting and receiving antennas are assumed to be installed on towers / buildings, at moderate height above the earth surface (meters or tens of meters), so that propagation in the lower atmosphere, close to ground, has to be considered.

Moreover, we assume that the radiowave frequency is in the range from UHF band (lower limit 300 MHz) up to some tens of GHz (60 GHz can roughly be the upper limit, according to present applications).

Compared with Free Space Propagation, the presence of the atmosphere and the vicinity of the ground produce a number of phenomena which may severely impact on radiowave propagation.

The major phenomena are due to:

- Atmospheric Refraction;
- Ray Curvature;
- Multipath Propagation;
- Interaction with particles/molecules in the Atmosphere;
- Atmospheric Absorption in the absence of rain;
- Raindrop Absorption and Scattering;
- Effects of the Ground:
- Diffraction through Obstacles;
- Reflections on flat terrain / water surfaces.

When one or more of the above phenomena affect radio propagation, the resulting impairment is:

- usually, an additional loss (with respect to free space) in the received signal power;
- in particular cases, also a distortion of the received signal.

Propagation impairments will be considered in the following sessions. In most cases they can be predicted only on a statistical basis. They are mainly affected by:

- Frequency of operation;
- Hop Length;
- Climatic environment and current meteorological conditions;
- Ground characteristics (terrain profile, obstacles above ground, electrical parameters).

From the viewpoint of the phenomena duration, let us consider:

- temporary impairments, which affect the received signal only for small percentages of time (examples are rain, multipath propagation, ...);
- long-term (or permanent) propagation conditions, which affect the received signal for most of the time (examples are atmospheric oxygen absorption, terrain diffraction, ...), even if their impact may be variable in some measure.

In most cases, long-term propagation impairments do not produce a significant power loss in the received signal, compared with Free Space conditions. So, the received power observed for long periods of time will be rather close to that predicted by the [Free Space Radio Link Equation](#).

The most significant exception to the above condition is experienced in radio paths with not-perfect visibility. In that case, attenuation caused by terrain diffraction results in a systematic loss, in comparison with Free Space conditions.

Link Budget

Even in designing Terrestrial Radio Links, the [Free Space Radio Link Equation](#) is the basis for received power prediction.

The equation in logarithmic units offers a very simple and convenient tool, since Gains and Losses, throughout the transmission chain, are added with positive or negative sign, as in a financial budget. The result is what is called the "Link Budget".

The Free Space equation can be re-written with more detail, taking account of actual equipment structure and of systematic impairments throughout the propagation path. An example is given in the Table below.

Power Level [dBm]	Gains [dB]	Losses [dB]
Tx Power at radio eq. output flange		
		Tx branching filter Tx feeder Other Tx losses
Power at ant. input		
	Tx antenna gain	
		Propagation losses : Free Space Obstruction Atm. Absorption Other
	Rx Antenna gain	
Power at ant. output		
		Rx feeder Rx branching filter Other Rx losses
Nominal Rx Power at radio eq.input flange		

As shown in the above example, the link budget includes an estimate of the power loss due to permanent (or long-term) impairments (like atmospheric absorption and obstructions). So, the Nominal Rx Power (as computed at the last line) is expected to be observed for long periods of time.

Once the Link Budget is computed, other impairments at the receiver are taken into account as:

- a degrading effect in receiver operation (Rx threshold degradation): this usually applies to the effect of ground reflections and interference;
- a short term attenuation (or even distortion) in the received signal, whose effect may be to fade the received signal below the Rx threshold

Power	Threshold	Margin
Nominal Rx Power		
	Equipment Threshold	
	Threshold Degrad. Reflections Interference	
	Hop Threshold	
		Fade margin

We summarize the final steps in Link Budget analysis with the two equations:

$$\text{Hop Threshold} = \text{Equipment Threshold} + \text{Threshold Degrad.}$$

$$\text{Fade Margin} = \text{Nominal Rx Power} - \text{Hop Threshold}$$

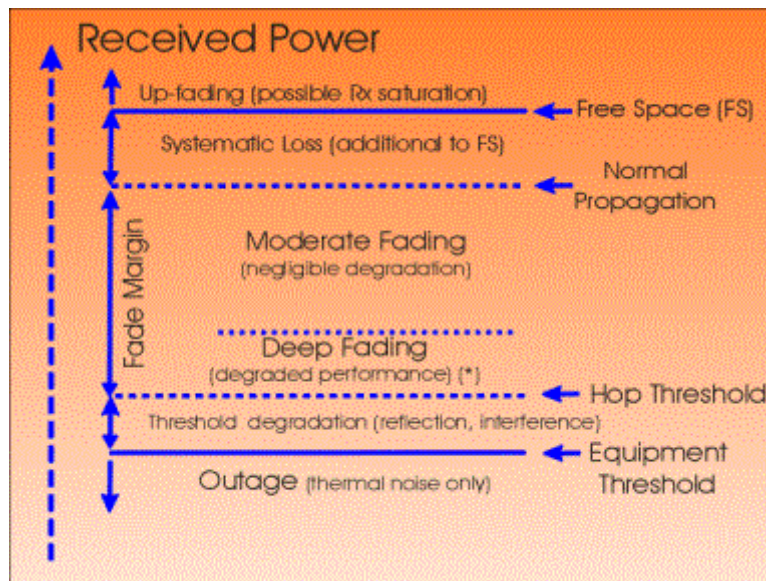
Note that Threshold Degradation causes the actual Hop Threshold to be higher than the Equipment Threshold (one dB threshold increase means one dB reduction in the available Fade Margin).

Fade Margin and Outage prediction

Typically, point-to-point radio hops are designed in a way that the Nominal Rx Power (as computed in the Link Budget) is far greater than the receiver threshold. So, rather large Fade Margins (of the order of 30-40 dB, or even greater) are usually available.

The Fade Margin is required to cope with short term attenuation and distortion in the received signal (mainly caused by rain and multipath).

A summary of various definitions is given in the diagram below.



A summary of definitions in Received Power levels, thresholds, and margins, with application to Outage estimation.

The above figure suggests the following comments:

- The Rx power may exceed the Free Space level: the so-called "up-fading" is a rather unusual event (it may be caused by particular refraction conditions, which create a sort of guided propagation through the atmosphere). Care must be taken that the received power level be in any case below the maximum level accepted by the Rx equipment (otherwise, receiver saturation and nonlinear distortion may be observed).
- The Rx Power will be at the Nominal level (Normal propagation) for most of the time.
- Moderate attenuation below the Nominal Rx power does not usually produce any significant loss in signal quality.
- The Equipment threshold may be degraded in some measure by reflections and/or interference, so that a higher Hop threshold must be considered.
- Starting from the very low Rx power, the Outage conditions are:
 - below the Equipment threshold, outage is produced by the receiver thermal noise, even in the absence of any additional impairment in the received signal;
 - below the Hop threshold, outage is caused by the combined effect of receiver noise and other impairments (like reflection or interference);
 - in the deep fading region, above the Hop threshold, outage may be observed when the received signal is not only attenuated, but also distorted by propagation events (mainly, frequency selective multipath).

From the above discussion, the Outage time, during the observation period T_o (typically, one month) can be predicted as :

$$\text{Outage Time} = T_o \cdot \text{Prob}\{\text{Rx Power} < \text{Hop Threshold}\}$$

if no contribution to outage is expected from signal distortion.

On the other hand, if significant distortion in the Rx signal is expected to contribute to the total outage, the prediction formula has to be completed as:

$$\text{Outage Time} = T_o \cdot [\text{Prob}\{\text{Rx Power} < \text{Hop Threshold}\} + \text{Prob}\{\text{Outage due to Distortion} / \text{Rx Power} > \text{Hop Threshold}\}]$$

where the second term gives the contribution to outage probability when the received signal is above the Hop threshold, but it is severely distorted (note that $\text{Prob}\{A/B\}$ means probability of event A, given that event B is true).

These formulas only help to clarify how the outage time is related to the Rx power level and to additional impairments in the received signal. They do not provide a practical means to predict outage time; this requires that suitable statistical models of propagation impairments be available: Such models will be considered in the following Sessions.

ADVANCED - Link Equation with Passive Repeater

When a Passive Repeater is used in a radio hop, we have to revise the "Basic Radio Link Equation".

To be consistent with the simple Free Space formula, we write the new equation as :

$$P_R = P_T + G_T + G_R - FSL(D_{TOT}) - L_{PR}$$

where :

$FSL(D_{TOT})$ is the Free Space Loss of a radio link with path length $D_{TOT} = \sum D_i$;

D_i is the length of each path leg;

L_{PR} is the power loss caused by the passive repeater, in comparison with the Free Space case.

Single Reflector - We refer to the path geometry, as shown in a previous figure and to the definition of the reflector effective area A_E . Then, L_{PR} is given by :

$$L_{PR} = 49.54 + 20 \log_{10} \frac{D_1 \cdot D_2}{D_1 + D_2} - 20 \log_{10}(F \cdot A_E)$$

where F is the working frequency in GHz and D_1, D_2 are the leg lengths in km.

Double Reflector - Again, we refer to the path geometry, as shown in a previous figure and to the definition of the reflector effective area A_E . Then, L_{PR} is given by :

$$L_{PR} = 99.08 + 20 \log_{10} \frac{D_1 \cdot D_2 \cdot D_3}{D_1 + D_2 + D_3} - 20 \log_{10}(F^2 \cdot A_{E1} \cdot A_{E2})$$

where F is the working frequency in GHz and D_1, D_2, D_3 are the leg lengths in km.

Back-to-Back antenna system - The path geometry is shown in a [previous figure](#). Then, L_{PR} is given by :

$$L_{PR} = 92.44 + 20 \log_{10} \frac{D_1 \cdot D_2}{D_1 + D_2} + 20 \log_{10}(F) - G_1 - G_2 + L_F$$

where F is the working frequency in GHz, D_1, D_2 are the leg lengths in km, G_1, G_2 are the antenna gains at the repeater site (usually $G_1 = G_2$) and L_F is the loss due to the feeder connecting the two antennas.

Near Field correction - The above formulas are correctly used when the reflectors are positioned outside the "near-field" region. If this condition is not satisfied, then a correction factor (additional loss) must be applied.

The near-field region is estimated as a function of the antenna and reflector dimensions and of the signal frequency (wavelength λ). Two normalized parameters (α, β) are computed :

$$\alpha = \frac{\pi \cdot \lambda \cdot D_{Min}}{4 \cdot A_E} \quad \beta = d \cdot \sqrt{\frac{\pi}{4 \cdot A_E}}$$

where D_{Min} is the shortest leg from one antenna to the closest reflector, d is the antenna diameter and A_E is the reflector effective area.

A rule of thumb is the following: for β in the range 0.2 - 1.5 (this covers most practical conditions), the near field correction factor is not negligible if $\alpha < (0.5 + \beta)$. Some examples are given in the Table below :

	$\beta = 0.2$	$\beta = 0.6$	$\beta = 1.0$	$\beta = 1.4$
$\alpha = 0.25$	4.6 dB	8.2 dB	9.5 dB	> 10 dB
$\alpha = 0.40$	1.7 dB	3.9 dB	7.1 dB	9.8 dB
$\alpha = 0.60$	0.7 dB	1.8 dB	3.8 dB	6.7 dB
$\alpha = 1.00$	< 0.5 dB	0.7 dB	1.6 dB	3.1 dB
$\alpha = 1.50$	< 0.5 dB	< 0.5 dB	0.7 dB	1.3 dB

This concludes Section 2 of the PPRLE. Please proceed to Herald Lab Exercise 2.

End of Section #2

SECTION 3 – PATH CLEARANCE

Summary

In this Session the effect of the atmosphere on radio ray trajectories is first considered, by introducing the k-factor concept; possible deviations from standard conditions are identified, as well as the minimum k-factor value. Then the Fresnel ellipsoid is defined; the partial obstruction of the ellipsoid leads to the estimate of the resultant loss. Finally, the previous concepts are used to set clearance criteria and to discuss their application to path profile analysis.

Refractivity in the Atmosphere

The Refractive Index n in a given medium is defined as the ratio of the speed of radio waves in vacuum to the speed in that medium. Since the speed of radio waves in the atmosphere is just slightly lower than in vacuum, then the Refractive Index in the atmosphere is greater than, but very close to, 1.

However, also small variations in the atmosphere Refractive Index have significant effects on radio wave propagation. For this reason, instead of using the Refractive Index n (close to 1), it is convenient to define the Refractivity N as :

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

So, N is the number of parts per million that the Refractive Index exceeds unity; it is a dimensionless parameter, measured in N-units.

The atmosphere Refractivity is a function of Temperature, Pressure, and Humidity. The ITU-R Rec. 453 gives the formula :

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

where :

T = absolute temperature (Kelvin deg);

P = atmospheric pressure (hPa, numerically equal to millibar);

e = water vapour pressure (hPa).

At sea level, the average value of N is about $N_0 = 315$ N-units. The ITU-R gives world maps with the mean values of N_0 in the months of February and August.

Temperature, atmospheric pressure, and water vapour pressure are not constant with height. This produces a Vertical Refractivity Gradient G (measured in N-units per km, N/km), defined as:

$$G = \frac{N_1 - N_2}{H_1 - H_2}$$

where N_1 and N_2 are the refractivity values at elevations H_1 and H_2 , respectively.

Under normal (standard) atmospheric conditions, Refractivity decreases at a constant rate, moving from ground level up to about 1 km height. This means that the Refractivity Gradient G is constant, the typical value being about -40 N/km.

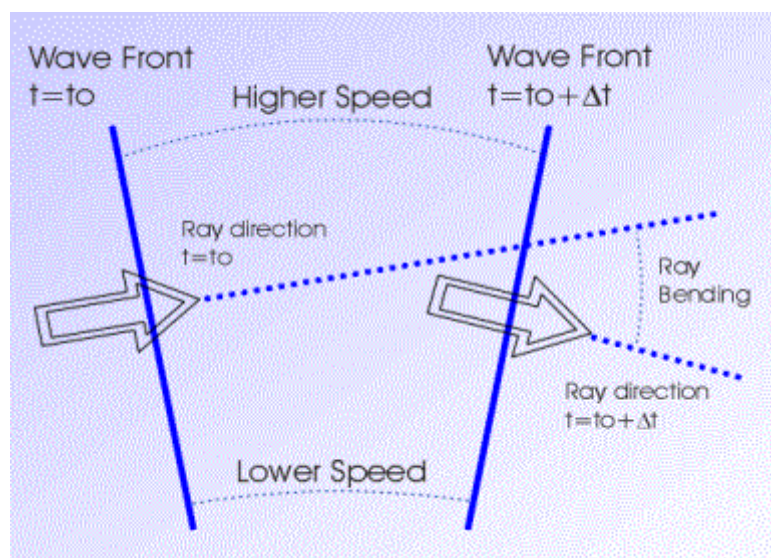
Deviation from the Standard Atmosphere condition is usually associated with particular weather events, like temperature inversion, very high evaporation and humidity, passage of cold air over warm surfaces or vice versa. In these conditions, the Vertical Refractivity Gradient is no longer constant. A number of different profiles have been observed and measured. It is worth noting that, at greater altitude, the Refractive Index is, in any case, closer and closer to 1; so the Refractivity N decreases to zero.

Propagation in Standard Atmosphere

A Radio Wave propagates in the direction normal to the iso-phase plane (the plane where all the points are phase synchronous, with respect to the sinusoidal pattern of electric and magnetic fields).

In a homogeneous medium, the iso-phase planes are parallel to each other and the propagation direction is a straight line normal to them.

As seen above, the Atmosphere is not a homogeneous medium and the Vertical Refractivity Gradient gives a measure of that. Different Refractivity at different heights means different propagation speeds. The wave-front moves faster or slower, depending on the height: this causes a rotation of the wave-front itself.



Wave-front and ray rotation caused by a vertical refractivity gradient in the atmosphere

So, the propagation trajectory (normal to the wave-front) is not a straight line, but it is rotated, as shown in the above figure. Taking into account that the propagation speed is inversely proportional to the refractive index, it is possible to derive that the radio trajectory curvature $1/r$ is related to the Vertical Refractivity Gradient G , as :

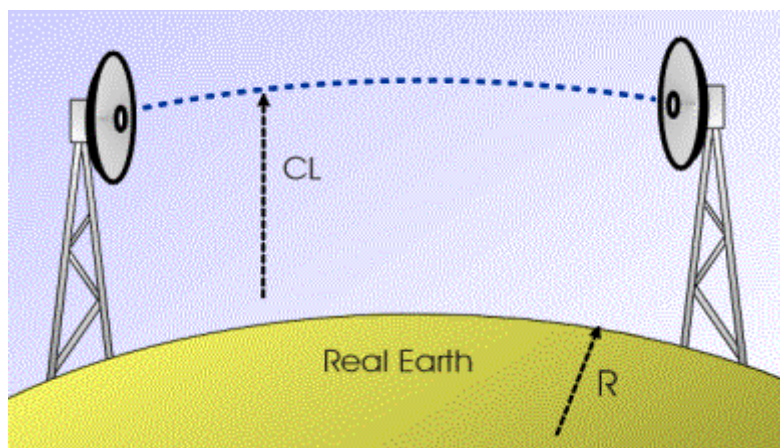
$$\frac{1}{r} = -G \cdot 10^{-6}$$

In Standard Atmosphere, with a typical value of the Refractivity Gradient $G = -40 \text{ N/km}$, the curvature of the radio ray trajectory is :

$$\frac{1}{r} = 40 \cdot 10^{-6} [\text{km}^{-1}]$$

This means that the radio ray is bent downward, with a curvature $1/r$, somewhat lower (less curved) than the Earth curvature $1/R$:

$$\frac{1}{R} = \frac{1}{6370 [\text{km}]} = 157 \cdot 10^{-6} [\text{km}^{-1}]$$



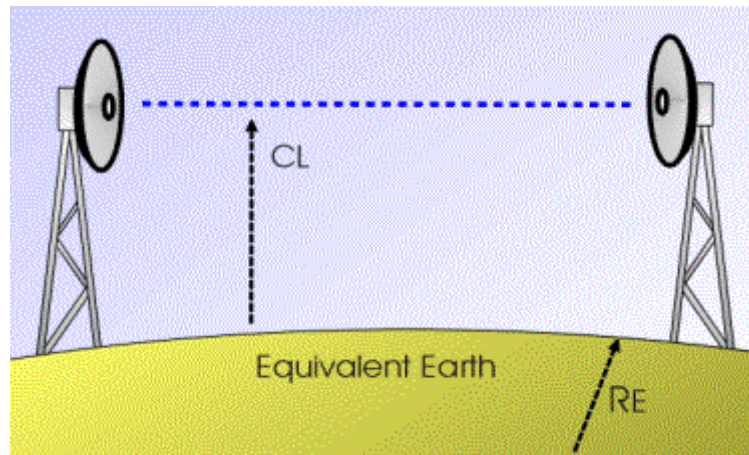
Ray bending in standard atmosphere (CL = clearance, vertical distance from ground to ray trajectory)

The k-factor

A convenient artifice is used to account, at the same time, for both the ray and the earth curvatures. An "equivalent" representation of [the above figure](#) can be plotted by altering both curvatures by an amount equal to the ray curvature $1/r$.

In the new figure (see below) the radio ray trajectory becomes a straight line, while the modified ("equivalent") earth curvature $1/R_E$ is :

$$\frac{1}{R_E} = \frac{1}{R} - \frac{1}{r}$$



Equivalent representation of [the previous figure](#), with a modified earth radius R_E and a straight ray trajectory.

Note that, at any point of the radio path, the vertical distance (CL = clearance) from the earth surface to the ray trajectory is the same in the real and in the equivalent representations.

The ratio between the equivalent and the real earth radius is defined as the "effective earth-radius factor k " (briefly, the k -factor). Taking account of previous formulas, giving $1/R_E$, $1/R$, and $1/r$, the k -factor is given by :

$$k = \frac{R_g}{R} = \frac{1/R}{1/R_g} = \frac{1/R}{1/R - 1/r} = \frac{157 \cdot 10^{-6}}{157 \cdot 10^{-6} - 1/r} = \frac{157}{157 + G}$$

In Standard Atmosphere ($G = -40$ N units/km), this gives :

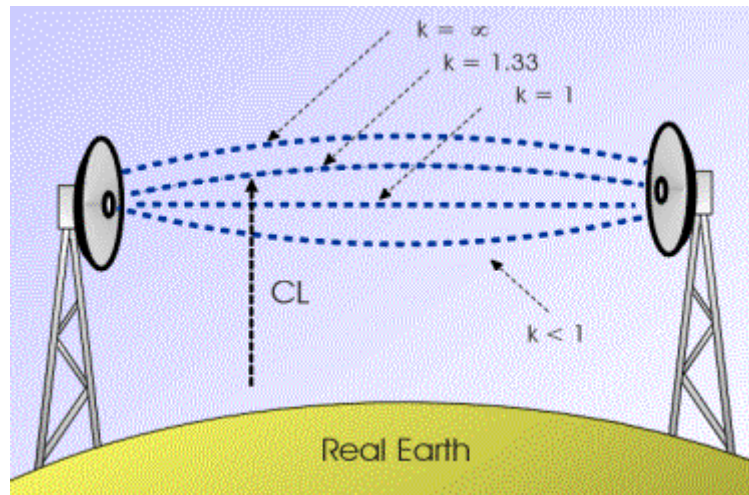
$$k \approx 1.33 \approx 4/3$$

The k -factor gives an indication about the atmosphere state at a given time and about the bending effect on the radio ray trajectory. So, the statement "propagation at $k = 4/3$ " is a synonymous of "propagation in Standard Atmosphere".

On the other hand, $k < 4/3$ corresponds to "Sub-refractive" conditions, in which the ray curvature is less than normal or even is an upward curvature ($k < 1$, $G > 0$), thus reducing the clearance over ground.

With $k > 4/3$ we are in a "Super-refractive" atmosphere; in particular, with $k = \infty$, the ray trajectory is parallel to the earth surface and the signal can propagate over large distances, beyond the normal horizon.

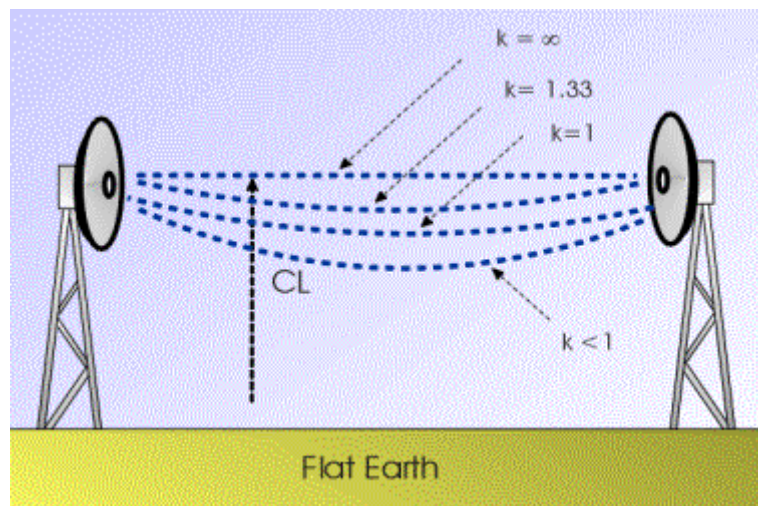
The figure below compares the ray trajectories with different k -factors, using a "real earth" representation.



Ray bending in different atmospheric conditions(different k-factor values)

A further alternative in plotting radio ray trajectories over the earth surface, is called "flat earth" representation

Again, both the earth and the ray curvature are altered, but in this case the earth profile is forced to be flat, while the ray curvature is modified accordingly. The "real earth" and the "flat earth" diagrams are equivalent in the sense that, at any point of the radio path, the vertical distance (CL = clearance) from the earth surface to the ray trajectory is the same in both representations.



Equivalent representation of the previous figure, over flat earth

Using the "flat earth" representation, we can plot on the same diagram the path profile and multiple rays, corresponding to different values of the k-factor. This is the most usual diagram shown in computer applications for radio hop design.

k-Factor variability

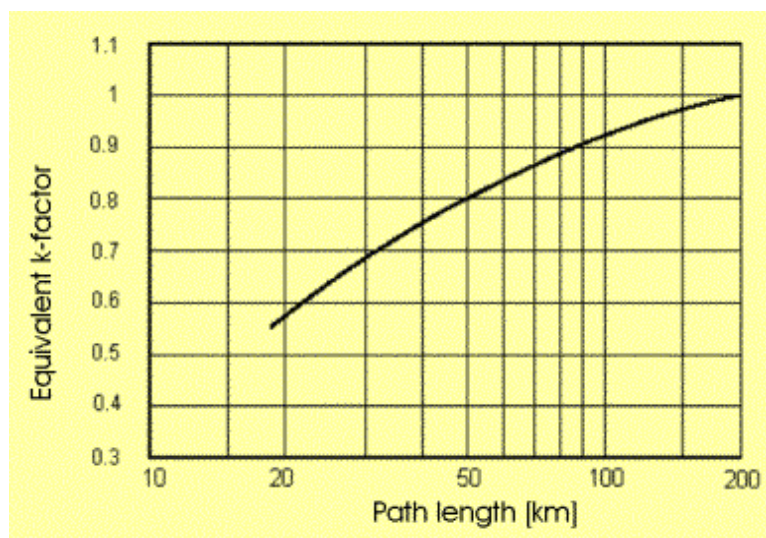
We have seen that the k-factor is related to the atmosphere state and is a function of the refractivity vertical gradient. So, it is a variable parameter, depending on daily and seasonal cycles and on current meteorological conditions. In a "standard atmosphere" state the k-factor value is 4/3; this is close to the median value in most climates (particularly, temperate climates). Around this median value, the range of variations is rather wide in tropical regions, with increasing temperature and/or humidity, while it is more limited in cold and temperate climates.

Experimental observations show for example that the probability of $k < 0.6$ in temperate climates is generally well below 1%. In tropical climates the same event is observed with probability in the range 5% - 10%. This means that, in tropical regions, there is the highest probability of propagation anomalies due to extreme k-factor values. The ITU-R gives world maps of the time percentage with $G < -100$ N-units / km ($k > 2.75$), in different months.

In discussing k-factor variability, as applied to radio hop design and to clearance criteria, we have to consider that:

- In sub-refractive conditions (minimum k-factor) the clearance over ground is reduced and the probability of obstruction is maximum.
- We are not interested in the minimum "local" k-factor, but in the overall effect through the whole radio path. So an "equivalent k-factor" (k_{ea}) is defined, whose minimum value depends (for given climatic conditions) on the path length. On long hops k_{ea} is likely to be not far from standard values, because extreme atmosphere conditions are probably not present at a time on the whole path, while in shorter hops it is more likely that particular events affect almost the whole path and produce lower k_{ea} values.

The ITU-R (Rec. P-530) gives a curve of minimum k_{ea} values as a function of hop length (temperate climate).



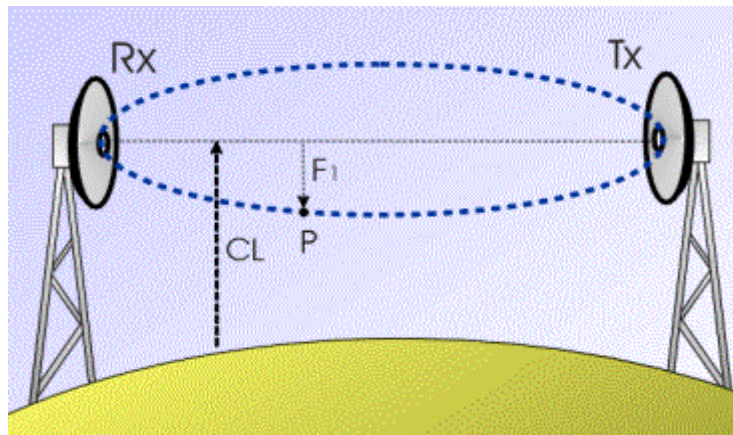
Minimum equivalent k-factor vs. path length (from ITU-R Rec. P-530, by IT permission).

Fresnel Ellipsoid

From a geometrical point of view, the Fresnel ellipsoid is defined as the set of points (P) in the space which satisfy the equation :

$$TxP + PRx = TxRx + \lambda / 2$$

where Tx and Rx are the two antennas (radio path terminal points), representing the two focuses of the ellipsoid.



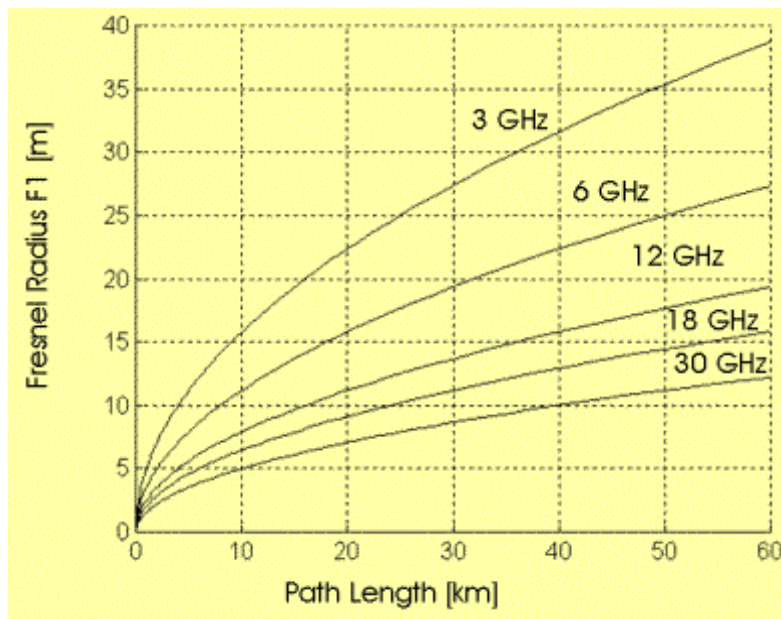
The Fresnel ellipsoid, F1 = ellipsoid radius; CL = clearance, measured from earth surface to the ray trajectory (that is the ellipsoid longitudinal axis)

The radioelectrical interpretation of the Fresnel ellipsoid is that two rays, following the paths Tx-Rx and Tx-P-Rx, arrive at the Rx antenna in phase opposition (half-wavelength path difference, then 180 deg phase shift).

The Fresnel ellipsoid radius F1 (in meters), at a distance D1 from one of the radio sites, is given by :

$$F1 = \sqrt{\frac{300 \cdot D1 \cdot (D - D1)}{D \cdot F}} = \sqrt{\frac{1000 \cdot \lambda \cdot D1 \cdot (D - D1)}{D}}$$

where D (km) is the path length, F (GHz) is the frequency and λ (m) is the wavelength. Some examples are given in the figure below; note that the Fresnel ellipsoid radius reduces as frequency increases.



Fresnel ellipsoid radius vs. path length and frequency (max radius, computed at mid path length).

From a practical point of view, the Fresnel ellipsoid gives a rough measure of the space volume involved in the propagation of a radiowave from a source (Tx) to a sensor (Rx). About half of the Rx signal energy travels through the Fresnel ellipsoid. So, any obstruction within the Fresnel ellipsoid has some impact on the Rx power level.

This leads to consider radio visibility in terms of clearance of the Fresnel ellipsoid, as discussed below.

A note on radio propagation and visual analogies

We are familiar with our visual experience and this can be of help in describing some aspects of radio propagation.

However, the Fresnel ellipsoid shows that radio propagation (like any EM propagation effect) cannot be explained only in terms of geometric optics, that is adequate so long as any discontinuities encountered through the propagation path are very large compared with the wavelength.

The ellipsoid radius is proportional to the wavelength square root. In our visual experience, the light wavelength is so small (about $5 \cdot 10^{-4}$ mm) that the radius of the Fresnel ellipsoid is negligible, at least as a first approximation. Diffraction effects can be observed only with accurate experiments, showing the role of Fresnel ellipsoid also in the optical field.

On the other hand, in radio communications the wavelength is in the range from 1 m (frequency 300 MHz) to about 1 cm (frequency 30 GHz), that is almost one million times larger than in visible waves.

In conclusion, much care must be paid in establishing an analogy between radio propagation and visual experience. Even if in both cases we deal with EM waves, the large difference in wavelength makes practical results quite different in most conditions. For example, the concept of Visibility is quite different in Radio Engineering and in our visual experience.

Obstruction Loss

At any point of the path profile, the Clearance (CL) is defined as the vertical distance from the ray trajectory to the ground. Since for different k-factor values a different ray trajectory is observed, then the Clearance at a given point depends on the k-factor (atmosphere state).

A negative Clearance means that an obstacle is higher than the ray trajectory (note that this is the sign convention used in ITU-R Rec. P-530, while the opposite is adopted in ITU-R Rec. P-526).

Single obstacle loss

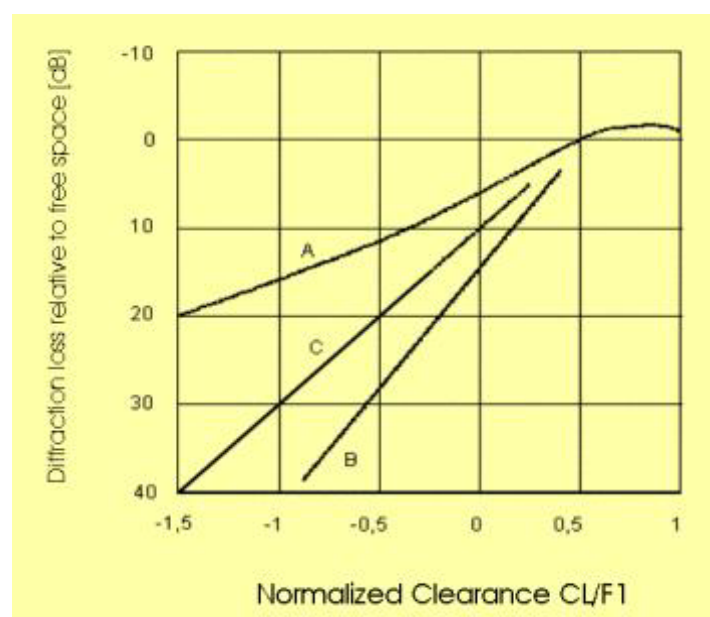
The effect of a single obstacle, that in some measure impedes the propagation of a radio signal, is analyzed in terms of Fresnel ellipsoid obstruction. So, a Normalized Clearance is defined as $C_{\text{NORM}} = CL / F_1$, where F_1 is the Fresnel ellipsoid radius.

A theoretical evaluation of diffraction loss is usually made with reference to two idealized obstacle models:

- the knife-edge obstruction, that is an obstacle with negligible thickness along the path profile;
- the smooth spherical earth, that is the obstruction produced by the earth surface for transmission beyond the horizon.

The two models represent extreme and opposite conditions and most practical cases can be assumed as intermediate between them.

The ITU-R Rec. P-530 gives obstruction loss curves (see below) for the two models mentioned above and for an intermediate case (the smooth earth result is for $k = 1.33$ and frequency 6.5 GHz).



Diffraction Loss vs. Normalized Clearance, with different obstacles: A) knife edge; B) smooth spherical earth; C) intermediate (from ITU-R Rec. P-530, by ITU permission)

Advanced - More on obstruction loss computation

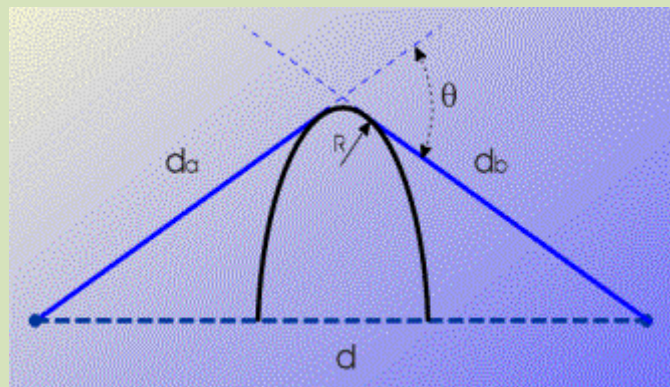
A more detailed analysis of obstruction loss is reported in ITU-R Rec. P-526, where general formulas are given. The knife-edge model is also extended to rounded obstacles and to the case of multiple obstructions.

Knife-edge obstacle - A good approximation of the obstruction loss produced by a knife-edge obstacle is given by :

$$L_{knife}(dB) = 6.9 + 20 \cdot \text{Log}_{10} \left[\sqrt{(v - 0.1)^2 + 1} + v - 0.1 \right]$$

where $v = -\sqrt{2} \cdot C_{NORM}$ and the approximation holds for $C_{NORM} < 0.5$.

Single rounded obstacle - The obstacle geometry is shown in the figure below, where also the relevant parameters are graphically defined.



Geometrical parameters in a rounded obstacle (from ITU-R Rec. P-526, by ITU permission).

An approximate formula for the obstruction loss is :

$$L_{rounded}(dB) = L_{knife} + \Delta L$$

where L_{knife} is given above and ΔL is the additional loss, compared with a sharp (knife-edge) obstacle, given by:

$$\Delta L(dB) = 7 \cdot (1 + 2v) \cdot p$$

The normalized parameters v and p are computed as:

$$v = 2 \cdot \sin\left(\frac{\theta}{2}\right) \cdot \sqrt{\frac{2 \cdot (d_a + R \cdot \theta/2) \cdot (d_b + R \cdot \theta/2)}{\lambda \cdot d}}$$

$$\rho^2 = \frac{d_a + d_b}{d_a \cdot d_b \cdot \sqrt[3]{\frac{\pi \cdot R}{\lambda}} \cdot \frac{1}{R}}$$

where λ is the signal wavelength and the geometrical parameters (d , d_a , d_b , R , θ) are defined in the [figure above](#).

The approximation holds for :

$v > 0$ that is for negative clearance (obstacle above the ray trajectory);

$\rho < 1$ that, for frequency above 1 GHz, means, in practical terms, that the obstacle should not be very close to one hop terminal.

Spherical earth - At frequencies above 1 GHz, the spherical earth formulas give :

$$L_{earth}(dB) = 11 + 10 \cdot \log_{10}(X) - 17.6 \cdot X + G(Y_1) + G(Y_2)$$

where :

$$X = 22 \cdot F^{1/3} \cdot R_E^{-2/3} \cdot D$$

$$Y = 0.96 \cdot F^{2/3} \cdot R_E^{-1/3} \cdot H$$

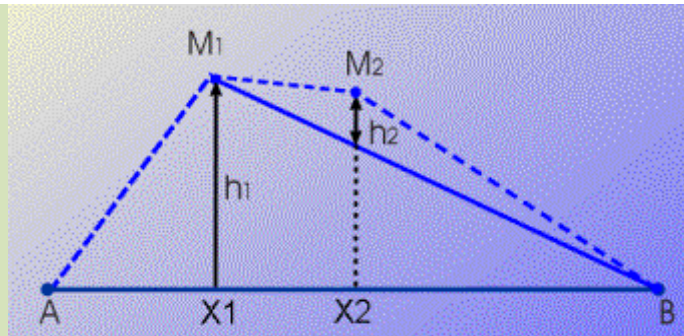
$$G(Y) = 17.6 \cdot (Y - 1.1)^{1/2} - 5 \cdot \log_{10}(Y - 1.1) - 8 \quad \text{for } Y > 2$$

$$G(Y) = 20 \cdot \log_{10}(Y + 0.1 \cdot Y^3) \quad \text{for } Y \leq 2$$

and finally F is the frequency (GHz), R_E is the equivalent earth radius (8500 km for $k = 1.33$), D is the path length (km), H is the antenna height (m) over the earth surface; Y_1 , Y_2 in the first formula refer to the first and second path terminal, respectively (in the Y formula, use the appropriate antenna height).

Multiple obstacles - Several approximate methods have been suggested to estimate the obstruction loss produced by multiple obstacles in a radio hop. It is to be noted that point-to-point links should be usually designed in such a way to avoid multiple obstacles along the radio path. However, it is useful to have computational techniques to deal also with this problem.

A reliable solution is the so-called Deygout model. Let us consider, at first, a path with two obstacles, as shown below.



Evaluation of two obstacle loss with the Deygout model (from ITU-R Rec. P-526, by ITU permission).

First, the clearance is estimated at each obstacle, as if that obstacle is the only obstacle in the path. So, the "most significant obstacle" is identified, as the obstacle producing the worst (most obstructing) clearance (in the example above, this corresponds to point M1).

The overall obstruction loss L_{TOT} is then estimated as :

$$L_{TOT} = L[AX1, X1B, h1] + L[X1X2, X2B, h2]$$

where $L[XY, YZ, H]$ is the knife-edge obstruction loss in a radio path from X to Z, where an obstacle is at point Y with height H.

The method can be iteratively extended to more than two obstacles. For the total radio path and then for each "sub-path", the most significant obstacle is identified.

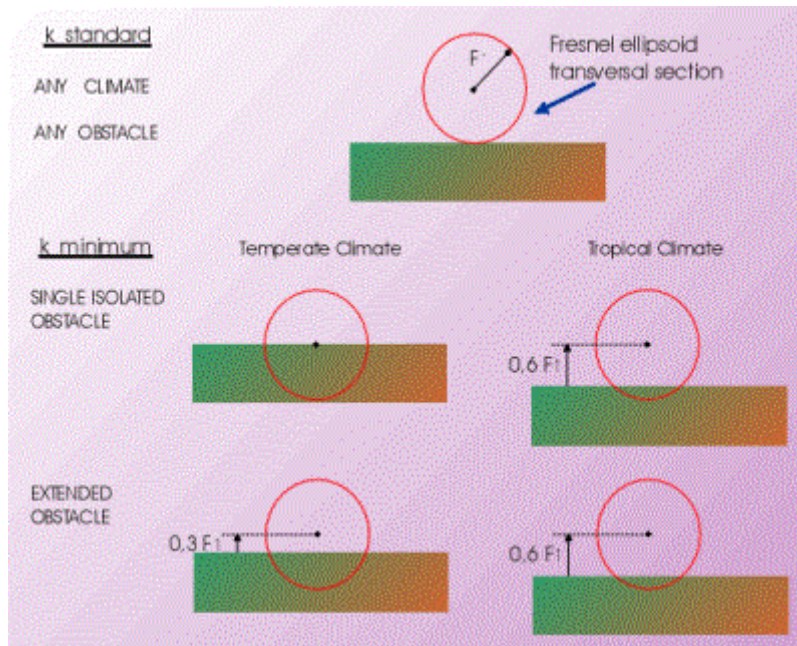
ITU-R Rec. P-526 applies the Deygout model to both knife-edge and rounded obstacles, with introduction of a correction factor (which is negligible when the obstacles are evenly spaced).

Clearance Criteria

We now have all the elements to establish Clearance Criteria in the design of a radio hop:

- the ray trajectory has been discussed and the minimum k-factor value (most critical condition) has been assessed;
- the loss produced by path obstructions has been evaluated as a function of the Normalized Clearance and using the Fresnel ellipsoid concept.

The Clearance Criteria given by ITU-R (Rec. P-530) are summarized in the figure below. They must be applied both in standard k and in minimum k conditions and take account of different climates and different obstacle shapes.



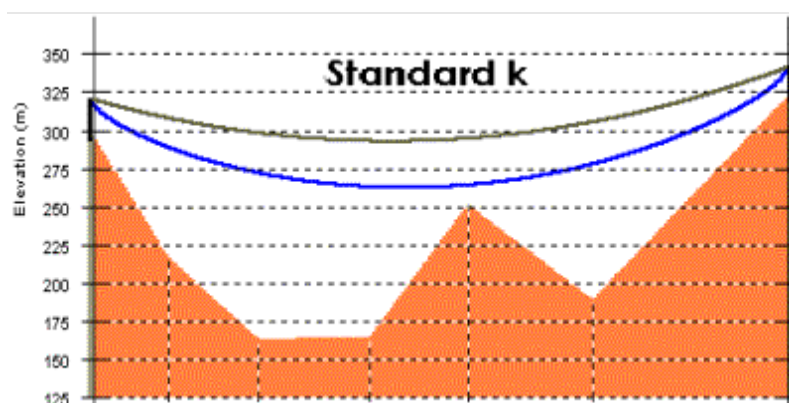
A chart showing the ITU-R (Rec. P- 530) criteria for path clearance. The red circle is the Fresnel ellipsoid transversal section, as seen from one hop terminal, partially obstructed by the ground.

The more stringent criteria for tropical climate are justified by the wider variability in k-factor values observed in those regions.

According to ITU-R, the above rules can be made less tight, in some measure, when frequencies below 2 GHz are used. This means that smaller fractions (by about 30%) of the Fresnel radius can be adopted.

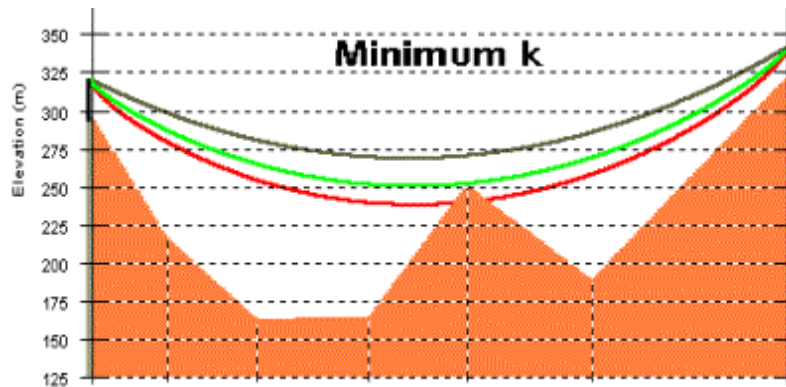
An example of application, with a single isolated obstacle, is given below, in a flat earth representation of the path profile; tropical climate is assumed. First, we check the standard-k condition (100% of the Fresnel ellipsoid free of obstacles). The two lines indicate:

- gray line: ray trajectory (ellipsoid axis) for $k = 1.33$;
- blue line: lower margin of the Fresnel ellipsoid (100% of the Fresnel ellipsoid radius).



Then we check the minimum-k condition (60% of the Fresnel ellipsoid free of obstacles). The three lines, in the figure below, indicates:

- gray line: ray trajectory (ellipsoid axis) for $k = k_{\min}$;
- red line: lower margin of the Fresnel ellipsoid (100% of the Fresnel ellipsoid radius);
- green line: 60% of the Fresnel ellipsoid radius.



The blue and the green lines, respectively in the two diagrams, are the limiting lines to satisfy the Clearance criteria (the vertical distance from such lines to the ground is usually indicated as the "Margin").

In most cases it is sufficient to indicate those two lines (as derived for k standard and minimum values) on the profile plot and to check that none of them intercepts the path profile (positive Margin).

This concludes Section 3 of the PPRLE. Please proceed to Herald Lab Exercise 3.

End of Section #3

SECTION 4 – GROUND REFLECTIONS

Summary

A radio path with ground reflection is examined. The reflection coefficient of different surfaces is discussed and several examples are given. The loss in received signal power is estimated, including the effect of antenna positioning and k-factor. Finally, the use of space diversity is considered and overall degradation is evaluated.

Paths with ground reflection

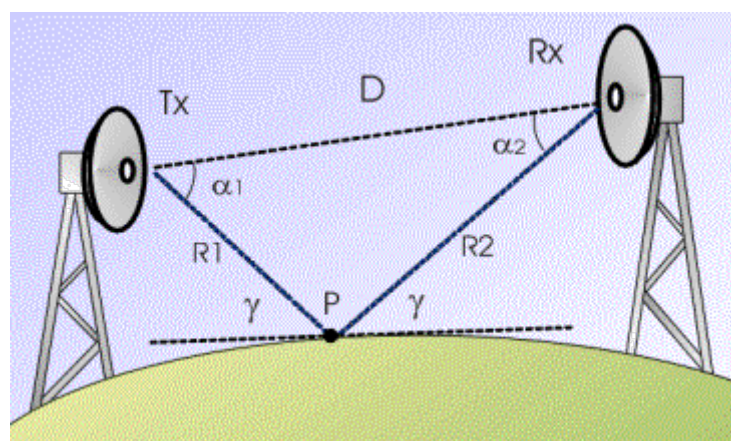
In radio hops over flat surfaces and particularly over the sea (or other large water surfaces), a fraction of the EM power emitted by the transmitter may reach the Rx antenna after reflection on the flat surface. So, at the receiver, the direct signal and the reflected signal (both coming from the same transmitter) may interfere each other.

Signal reflections represent in most cases a critical aspect of radio hop design and a potential source of operating problems, if not correctly evaluated at the design stage.

In route planning and site selection, a priority objective should always be to avoid hops with possible ground reflections, as far as possible. Obviously, alternative routes may be possible only in limited cases.

A careful selection of site positioning and antenna height may be of help in situations where such solution makes the reflected ray obstructed, at least partially. While discussing on received signal level, it will be shown that any technique, that reduces in some measure the reflected signal level, is useful in reducing the overall impact of signal reflection.

The first step in reflection analysis is to get all the geometrical elements useful to describe the reflection mechanism. The figure below gives a sketch of a radio path with ground reflection, showing the main geometrical parameters.



Path with ground reflection, main geometrical parameters.

- P = Reflection point;
- γ = Grazing angle;
- D = Direct path length;
- $R1+R2$ = Reflected path length;
- $\Delta L = R1+R2 - D$ = path length difference;
- α_1, α_2 = Angles between Direct and Reflected rays at the two antennas.

Reflection coefficient

By comparing the reflected radio wave to the incident one, amplitude and phase modifications are observed. The reflection coefficient is a complex number, where:

- the coefficient modulus is the amplitude ratio between the reflected and the incident signals; it represents the signal attenuation due to the reflection effect only;
- the coefficient phase gives the phase shift produced by reflection (phase difference between the reflected and the incident signals).

The reflection coefficient is a function of:

- signal frequency and polarization;
- grazing angle;
- electrical parameters of the reflecting surface (relative permittivity and conductivity; diagrams are given in ITU-R Rec. P-527 for different surface types: water, dry soil, wet soil, etc.).

Additional attenuation is caused by surface roughness, depending on soil irregularities or sea waves. However, smooth surface parameters usually represent a worst case assumption, with minimum loss.

Summary of results

At very low grazing angles ($\gamma < 0.2$ deg), the reflection coefficient amplitude, on sea surfaces or wet soil, is close to unity (0 dB) for both vertical and horizontal polarization; the phase is close to 180 deg.

For horizontal polarization (any frequency), the above results are almost unchanged when γ increases up to about 4 deg (higher values of the grazing angle are very unlikely).

On the other hand, with vertical polarization and the same range of the grazing angle, the reflection coefficient amplitude decreases to about 0.3 - 0.5 (-10 to -6 dB, the lowest loss being applicable to frequencies above 10 GHz). Also the phase decreases to 120° - 140° for frequencies in the 1 - 3 GHz range, while it is closer to 180° range for frequencies above 10 GHz.

While the above results only give approximate indications on the actual numbers to use in path design, it must be realized that the variable environment (for example, wet or dry soil) and the surface roughness make it difficult even to apply specific models and formulas to predict the reflection coefficient.

In most cases, it is advisable to make use of worst case assumptions for the coefficient amplitude, while not always a precise prediction on the phase shift is required (as explained below).

Advanced - Reflection coefficient computation

For a plane surface, the reflection coefficient Γ can be computed, according to the Fresnel law, as :

$$\Gamma_V = \frac{\eta \cdot \sin \gamma - \sqrt{\eta^2 - \cos^2 \gamma}}{\eta \cdot \sin \gamma + \sqrt{\eta^2 - \cos^2 \gamma}} \quad \text{Vertical polarization}$$

$$\Gamma_H = \frac{-\sin \gamma - \sqrt{\eta^2 - \cos^2 \gamma}}{-\sin \gamma + \sqrt{\eta^2 - \cos^2 \gamma}} \quad \text{Horizontal polarization.}$$

where

$\eta = \epsilon_r - j60\sigma\lambda$ is called complex permittivity, γ is the grazing angle, λ [m] is the signal wavelength, while the electrical parameters of the reflecting surface are :

ϵ_r relative dielectric constant;

σ electrical conductivity.

The expressions giving the reflection coefficient Γ can be specialized to the most common reflecting surfaces, taking account of typical values of the surface electrical parameters at different frequencies, as shown in the Tables below.

Relative dielectric constant ϵ_r (dimensionless parameter) :

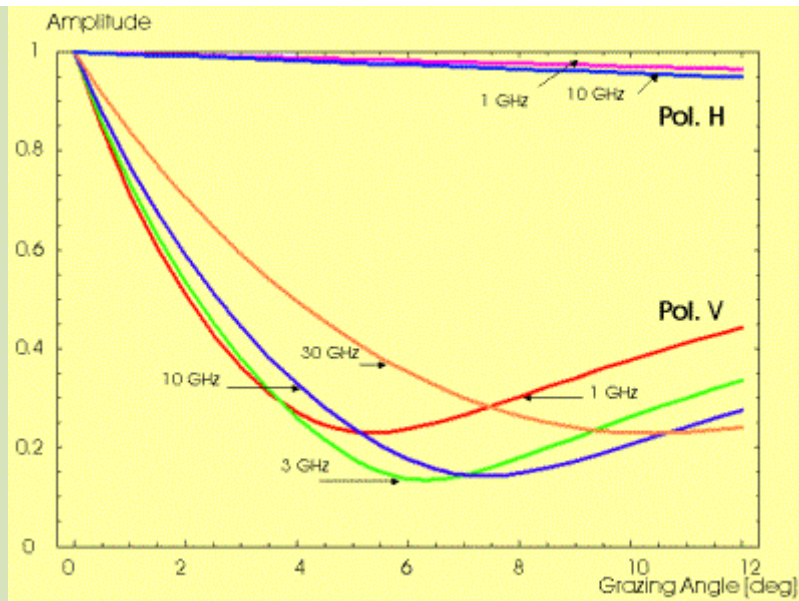
	1 GHz	3 GHz	10 GHz	30 GHz

Sea water	70	70	50	18
Fresh water	80	80	70	28
Wet ground	30	24	12	5.4
Very dry ground	4	4	4	4
Ice (-1 -10 °C)	4	4	4	4

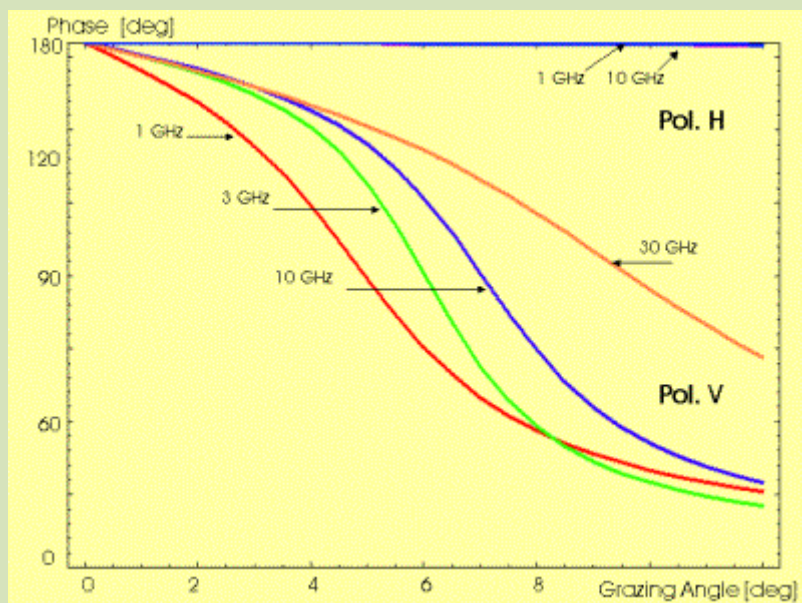
Electrical conductivity σ [ohm⁻¹ m⁻¹] :

	1 GHz	3 GHz	10 GHz	30 GHz
Sea water	5	7	18	40
Fresh water	0.18	1.8	16	40
Wet ground	0.15	0.7	3.2	11
Very dry ground	$1.5 \cdot 10^{-4}$	0.003	0.05	0.35
Ice (-1 -10 °C)	$2.5 - 8 \cdot 10^{-4}$	$0.6 - 2 \cdot 10^{-3}$	$2 - 6 \cdot 10^{-3}$	$0.5 - 1.7 \cdot 10^{-2}$

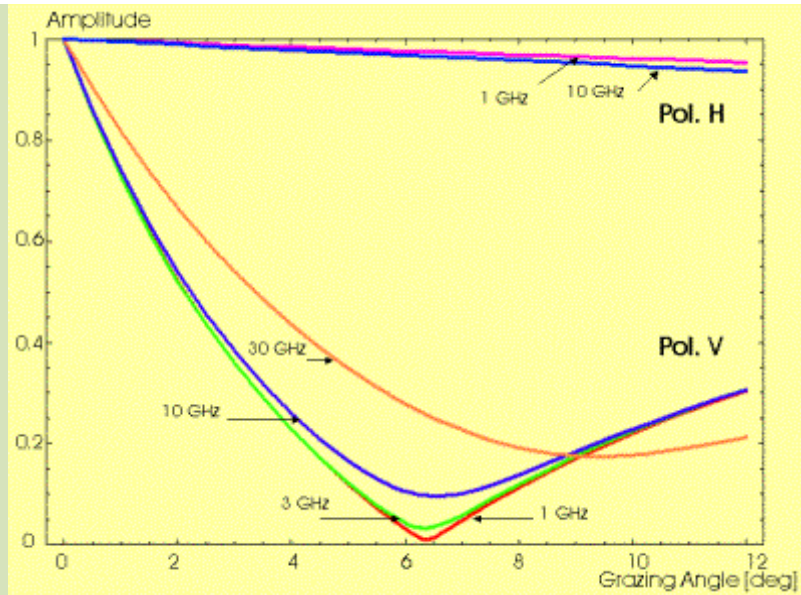
Example of results are shown in the figures below.



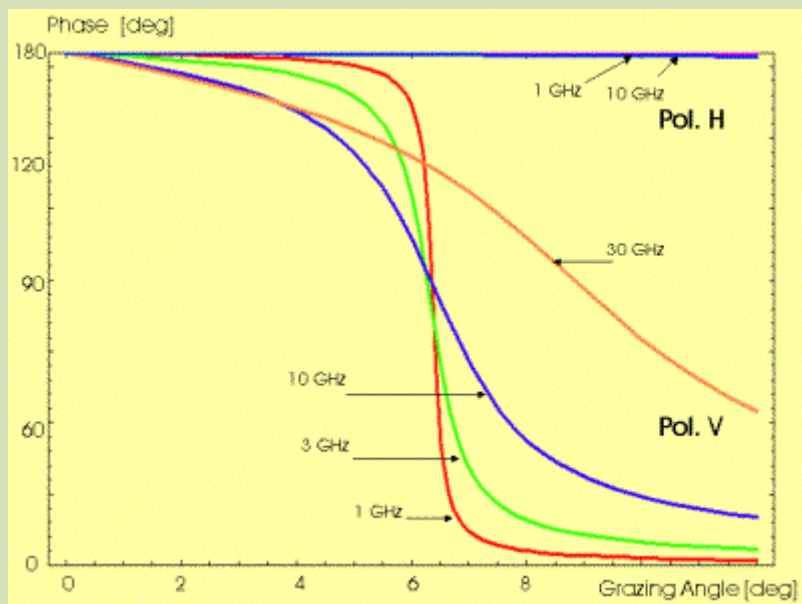
Reflection over the sea surface Amplitude of the reflection coefficient vs. grazing angle.



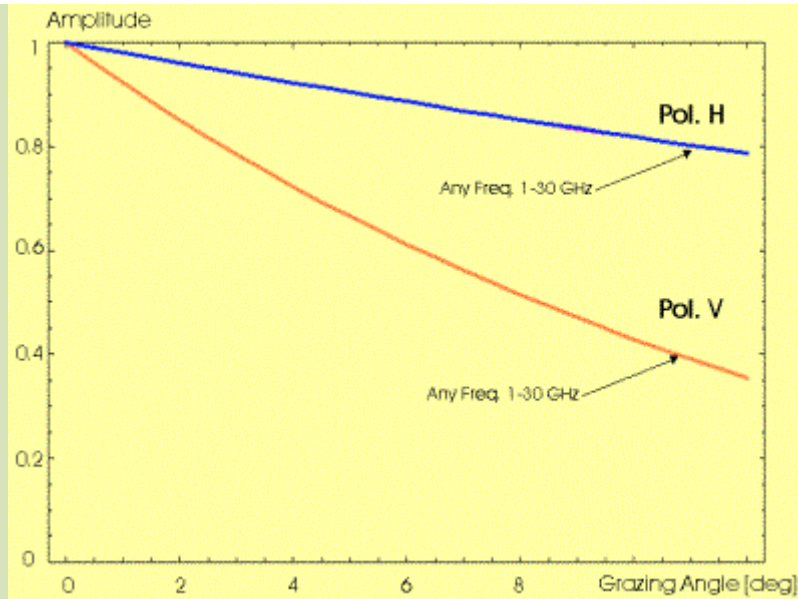
Reflection over the sea surface Phase of the reflection coefficient vs. grazing angle.



Reflection over a fresh water surface Amplitude of the reflection coefficient vs. grazing angle.



Reflection over a fresh water surface Phase of the reflection coefficient vs. grazing angle.



Reflection over very dry soil Amplitude of the reflection coefficient vs. grazing angle (the phase is close to 180° for both H and V polarization).

Received signal level

The Rx signal power results from the addition of the Direct and the Reflected signals

Vectorial addition of two signals

We measure "relative" signal amplitude and power as referred to the direct signal only. The Relative Rx Power (RRP, in dB), in the presence of a reflected ray, is :

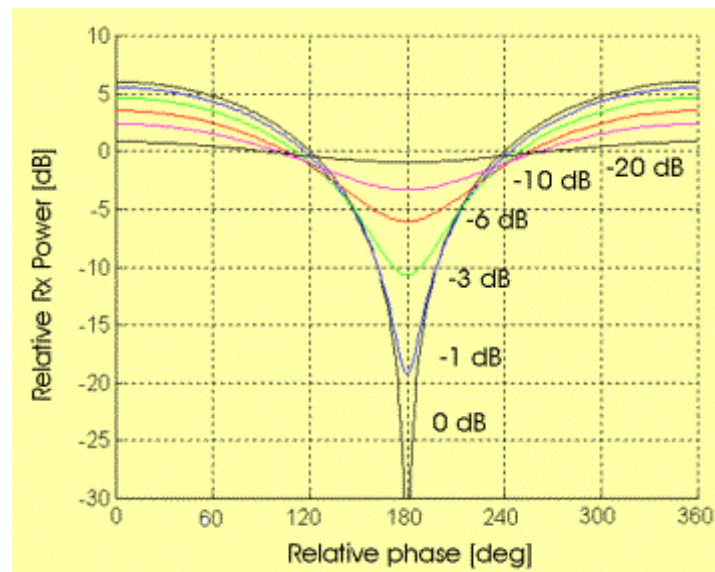
$$RRP = 10 \cdot \text{Log}_{10} [1 + b^2 + 2b \cdot \cos \beta]$$

where b , β are the relative amplitude and phase of the reflected ray, at the receiver input.

The relative power (B , in dB) of the reflected signal is :

$$B = 10 \cdot \text{Log}_{10} (b^2)$$

The figure below gives some examples of the result of the vectorial addition of two signals, with different amplitudes and varying relative phase.



Received signal power in the presence of a reflected signal, whose relative power B is indicated by the labels (relative power is referred to the direct signal alone).

As expected, if the direct and the reflected signals have equal amplitude (0 dB curve), then the resulting signal fades completely when the two signals are in phase opposition (relative phase 180 deg). On the other hand, if the reflected signal is more and more attenuated ($B = -10, -20$ dB curves), then the overall Rx signal shows a moderate fluctuation, as a function of the relative phase between the direct and the reflected signals.

Reflected signal amplitude

In order to estimate the relative amplitude of the two signals, we have to identify the additional attenuation in the reflected signal, compared to the direct one. Additional attenuation is mainly caused by:

- Reflection coefficient: as discussed above, it depends on signal frequency and polarization, grazing angle and surface electrical parameters; for reflection over water, the 0 dB loss (perfectly reflecting surface) may be a worst case assumption.
- Divergence factor: this is a geometrical factor, which accounts for the spherical shape of the reflecting earth surface, producing a divergence in the reflected beam (not negligible in reflection paths with very small grazing angle).
- Antenna gain reduction: assuming that the antenna is pointed in the direct ray direction, then the gain in the reflected ray direction is given by the antenna diagram at angles α_1 and α_2 (see reflection geometry); quite often these angles are very small, but in some cases (e.g. short hops with antennas very high over the reflecting surface) they produce a not negligible reduction in the antenna gain. Even in absence of the complete antenna diagram, the 3dB antenna beamwidth in the vertical plane can be sufficient to estimate the reduction in antenna gain for a small deviation from the antenna axis.

- Obstruction loss (if the reflection path is not perfectly clear): in most cases it can be estimated as a "knife edge" obstruction, because this is a conservative assumption and it is usually close to the actual conditions.

Reflected signal phase

On the other hand, the phase shift between the direct and the reflected signals depends on:

- Path length difference ΔL : this distance is converted into a phase shift, taking into account that a signal wavelength λ corresponds to a 360 deg phase rotation:

$$\delta = \Delta L \cdot 360 / \lambda \text{ [deg]}$$

- Reflection coefficient phase: as discussed above, in most cases it is close to 180 deg (phase reversal).

Rate of change in the Rx signal amplitude

Since the wavelength λ is of the order of centimeters, then in most cases $\Delta L \gg \lambda$. In such conditions, the above formula shows that a fractional change in ΔL (as caused even by small k-factor variations) produces a significant rotation of the δ phase. The final effect is that:

- the direct and the reflected signals add with a variable phase shift, which can be assumed as a random variable; amplitude fluctuations are to be expected in the sum signal (received signal);
- the reflection coefficient phase is not so important to be predicted, since it adds to the (randomly) variable phase shift δ ;

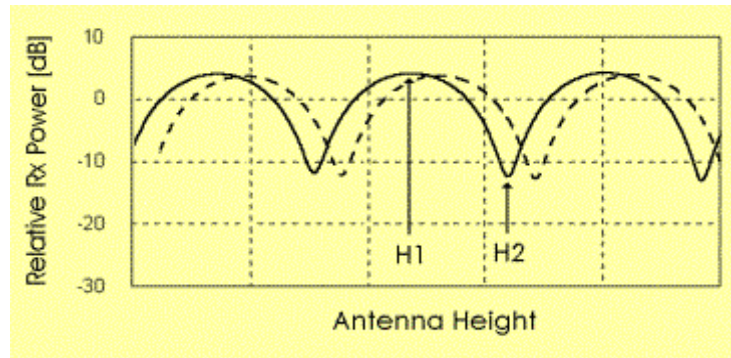
On the other hand, when ΔL is of the same order of magnitude of (or even smaller than) λ , a fractional change in ΔL produces a small rotation of the δ phase. So, in the vectorial addition of the direct and reflected signals, the phase angle is almost constant and slow variations in the Rx power level are likely (low levels may persist for long periods of time).

Antenna height and k-factor effect

The above discussion shows that the reflected signal amplitude and phase (relative to the direct one) are functions of the geometrical reflection parameters. So, we expect that

- the overall Rx signal level is a function of antenna position;
- for a given antenna position, the Rx signal level is time variable, due to atmospheric variations (changing k-factor);
- in particular cases, a time-variable Rx level may be also produced by variations in the reflecting surface (for example, tide movements).

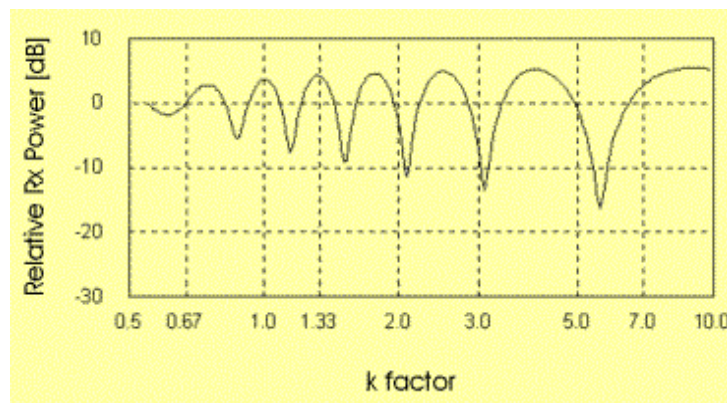
The figure below (continuous line) shows the Rx power level vs. antenna position. For a given antenna height (H_1) the two signals (direct and reflected) add in phase, so that the Rx signal level is maximum, while for a different antenna position (H_2) the two signals are in phase opposition and the Rx level is minimum.



Received signal power vs. antenna height, with two values of the k-factor (continuous and dashed lines) relative power is referred to the direct signal alone).

The dashed line refers to a different atmosphere condition (different k-factor) and shows that, even if the plots are similar, the antenna positions corresponding to max / min Rx signal power are not stable.

The effect of varying atmospheric conditions (k-factor) is presented in the figure below. At a constant antenna height, the received signal level may be at a maximum or minimum value, depending on variations in the k-factor.



Received signal power vs. k-factor, for a given antenna height (relative power is referred to the direct signal alone).

Note : The examples given in the previous figures are for a given reflection geometry, working frequency, etc. Other patterns in the Rx power diagrams may be found with different parameters. However, the comments suggested by these figures hold in most applications.

In summary:

- we cannot predict the exact antenna position corresponding to maximum or minimum Rx power levels (since this is not a static conditions, due to k-factor variations);

- we can however compute the Rx power range (vs. antenna position and k-factor);
- we can also compute the vertical distance ($H_2 - H_1$) between the antenna position for maximum Rx power and minimum Rx power.

Diversity reception

Generally speaking, we implement a diversity system by using two different communications channels to transmit the same information. At the receiver, the signals at the output of the two channels are processed to get a reliable estimate of the transmitted information. Basically, two techniques can be used:

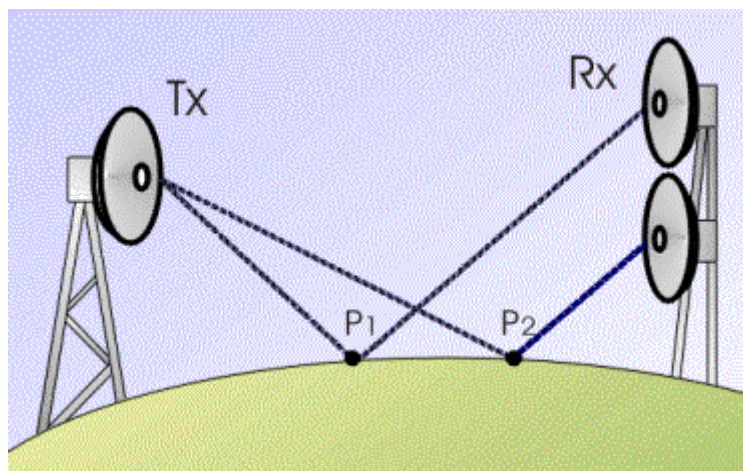
- the selection of the signal that, at a given time, is estimated to offer the best quality (diversity switching);
- the joint processing of the two signals (diversity combining).

A number of alternative implementations have been studied for each of the above techniques, taking account of different operating contexts and design constraints.

In any case, the basic requirement for effective diversity systems is that of a low correlation between the two channels, so that a low probability exists that both channels are in a bad state at the same time.

In radio paths with ground reflection, the two different communications channels can be implemented by using two vertically separated antennas at the receiver site (space diversity).

The reflection geometry is different for the two channels (different reflection point P_1 and P_2 , see figure below). So, it is expected that different signal levels are received at the two antennas, at a given time.



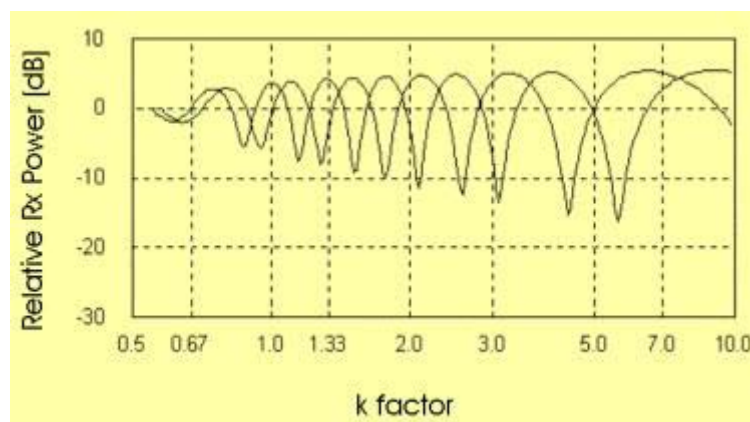
Space Diversity reception in a radio hop with ground reflection

In order to find the optimum vertical spacing between the two antennas, we compute the spacing $\Delta H = (H_2 - H_1)$ between a maximum and a minimum in the [Rx power vs. antenna height diagram](#).

With antenna spacing ΔH , it is expected that, while the Rx power level is minimum at one antenna, it is close to the maximum at the other antenna, and vice versa. So, both antennas are never in bad reception at the same time.

This estimate of the optimum spacing applies to a given k-factor value. As a first guess, the ΔH spacing is computed with the standard k value (1.33). Depending on the reflection geometry, this choice may be appropriate (or not) also for different k values.

The figure below shows the Rx power at the two antennas vs. k-factor. It gives a simple way to check how the antenna spacing, computed for a given k, works with other k values.



Same figure as above, with a diversity antenna added; optimum diversity spacing computed for $k = 1.33$ (relative power is referred to the direct signal alone).

In this example, we see that at least one of the two antennas receives a high power level for any k value greater than 1 (the max/min patterns of the two diagrams are well interleaved). On the other hand, going to low k values ($k < 1$), the two diagrams are closer and almost overlapping, so the diversity effect vanishes.

If the antenna spacing, optimized for standard k-factor, is not effective for other k-factors, possible suggestions are:

- to find a compromise solution, taking account of the likely range of k-factor values;
- to revise (if possible) the overall reflection geometry (for example, by modifying the antenna height also at the other hop terminal).

In implementing a space diversity configuration, usually the additional (diversity) antenna is installed below the main antenna. The clearance rules for the main antenna are as indicated in the [Path Clearance session](#).

For the diversity antenna, ITU-R Rec. P-530 gives the following clearance criteria:

- Normalized clearance $C_{NORM} > 0.3$ for an isolated obstacle;
- Normalized clearance $C_{NORM} > 0.6$ for an obstacle extended along a portion of the path.

The above limits may be reduced to 0.0 and 0.3, respectively, "if necessary to avoid increasing heights of existing towers" and if the frequency is below 2 GHz.

Performance degradation

In the previous chapters, the received signal power has been estimated for single and diversity reception, as a function of antenna positioning and atmospheric state (k-factor).

Under some aspects, it is necessary to make worst case assumptions, for example in the estimate of the reflection coefficient.

An overall estimate of performance degradation caused by ground reflection requires that the Rx power loss be averaged over the whole range of operating conditions.

The average loss in Rx signal power is estimated for a given k-factor, by assuming the phase shift between the direct and the reflected signals as a random variable. Moreover, it is possible to further average, over the expected range of k-factor variations.

Note that the signal phase shift can be assumed as a random variable only if $\Delta L \gg \lambda$ (path difference much larger than wavelength); this assumption has been discussed previously.

When diversity reception is adopted, a similar average can be performed but, for each operating conditions (k-factor value, signal phase shift), the antenna with the higher signal is selected. This is equivalent to a diversity system with ideal and instantaneous switching to the best signal; therefore, the results computed under the above assumptions may be optimistic in some measure.

Advanced -Average degradation estimate

The Rx signal power loss ($LOSS_{REFL}$), in the presence of a reflected ray, is given by the ratio of the direct signal power (normalized to 1) to the Rx power with reflection :

$$LOSS_{REFL} = \frac{1}{1 + b^2 + 2b \cdot \cos \beta}$$

where b, β are the relative amplitude and phase of the reflected ray, at the receiver input.

When, for a given reflection geometry and atmospheric state (k-factor), we can assume β as a random variable (see comments on the rate of change in the Rx signal amplitude), then the $LOSS_{REFL}$ average over the β uniform distribution is given by (the bar over a symbol means "average value") :

$$\overline{LOSS}_{REFL} = \frac{1}{2\pi} \int_0^{2\pi} \frac{1}{[1+b^2+2b \cos \beta]} \cdot d\beta = \frac{1}{1-b^2}$$

(the integral solution is not immediate and requires some careful mathematical processing).

Finally, the Threshold Degradation due to reflection D_{REF} (in dB) is given by :

$$D_{REF} = 10 \cdot \text{Log}_{10} [\overline{LOSS}_{REFL}] = 10 \cdot \text{Log}_{10} \left[\frac{1}{1-b^2} \right]$$

In more general terms, it is also necessary to further average the Rx signal power loss $LOSS_{REFL}$, over a range of likely k-factor values, since the reflection geometry (and specifically the reflected ray amplitude b) is a function of k. Then we need to estimate an integral expression of the type:

$$\overline{LOSS}_{REFL} = \frac{1}{k_{MAX} - k_{min}} \int_{k_{min}}^{k_{MAX}} \frac{1}{1-b^2(k)} \cdot dk$$

This is usually possible only by numeric integration methods.

In digital radio systems, additional degradation may be caused by signal distortions, when the time delay of the reflected signal is comparable with the symbol period of the digital modulation. This is not a usual condition, but it is to be considered with some care.

Advanced - Effect of time delay on digital signals

In digital radio links, it is necessary to compare the reflected signal delay τ with the symbol period T_s , in order to estimate the reflection impairment on the digital modulation.

When $\tau \ll T_s$ there is no significant distortion of the digital signal format, since the modulated pulses in the direct and reflected signals are almost overlapping at the receiver; the only reflection impairment is due to the Rx signal attenuation, as discussed previously.

If τ is comparable (\approx) with T_s , then the two-path (direct plus reflected signals) channel transfer function produces a frequency-selective distortion on the signal spectrum. The equipment signature gives a measure of the additional reflection impairment, due to Rx sensitivity to signal distortion.

Finally, the condition $\tau > T_s$ is very unlikely. However, in this case, the reflected signal appears as an external co-channel interference, since the modulation applied to the direct signal is not coincident with the modulation in the reflected signal. The equipment BER vs. C/I curve gives a measure of performance degradation under this condition.

This concludes Section 4 of the PPRLE. Please proceed to Herald Lab Exercise 4.

End of Section #4

SECTION 5 – MULTIPATH FADING

Summary

In this Session multipath propagation is considered. First, refractivity conditions are discussed and the received signal impairments are presented (signal attenuation and distortion). Multipath activity statistics are described, according to the Rayleigh model, and the multipath occurrence factor is defined. These models are applied for outage prediction, for both narrow-band and wide-band systems. Finally, multipath countermeasures, space and frequency diversity, are considered.

Refractivity in the atmosphere (II)

A general introduction to the effect of the atmosphere refractive index on radio propagation and specifically of a vertical refractivity gradient has been given in a previous Session.

In that context, we mainly considered constant gradient conditions, and we defined the "standard atmosphere" as the condition with vertical refractivity gradient $G = -40$ N/km (k -factor = 1.33). Still under the assumption of a constant refractivity gradient, other conditions are the "sub-refractive atmosphere" ($G > -40$ N/km; $k < 1.33$) and the "super-refractive atmosphere" ($G < -40$ N/km; $k > 1.33$).

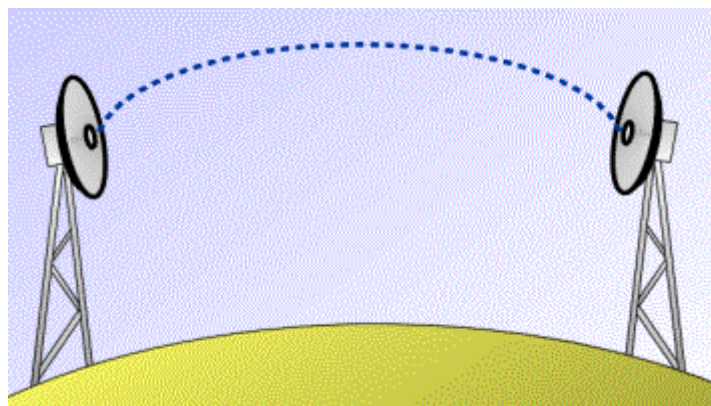
A constant vertical refractivity gradient means that the ray trajectory suffers the same curvature, at any elevation in the atmosphere. Under this condition, a direct ray trajectory is identified, from the Tx antenna to the Rx antenna, with launching angle α given by:

$$\alpha = -\arctg\left(\frac{H_T - H_R}{\beta} + \frac{\beta}{2 \cdot R_E}\right)$$

where

$$\beta = \sqrt{D^2 - (H_T - H_R)^2}$$

R_E is the equivalent earth radius (8500 km with standard k -factor = 1.33), H_T and H_R are the antenna heights at the transmitter and receiver, respectively, and D is the path length.

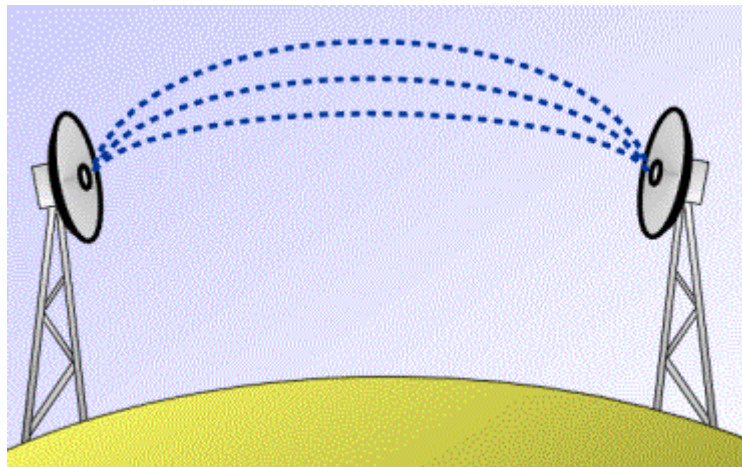


Ray trajectories in "constant gradient" atmosphere

More generally, the vertical refractivity gradient may deviate from a constant-gradient model. It may be assumed as constant within atmospheric layers of limited height (stratified atmosphere). In the real case, the transition from one layer to another is smoothed in some measure.

A stratified atmosphere model is useful in explaining the different bending of ray trajectories, when they travel at different elevations in the atmosphere.

In these conditions, the "gradient profile" may be such that not only a direct ray, but multiple rays, with different launching angles, reach the receiver antenna through several spatially disjointed paths. This is called "multipath propagation".



Ray trajectories under multipath propagation conditions

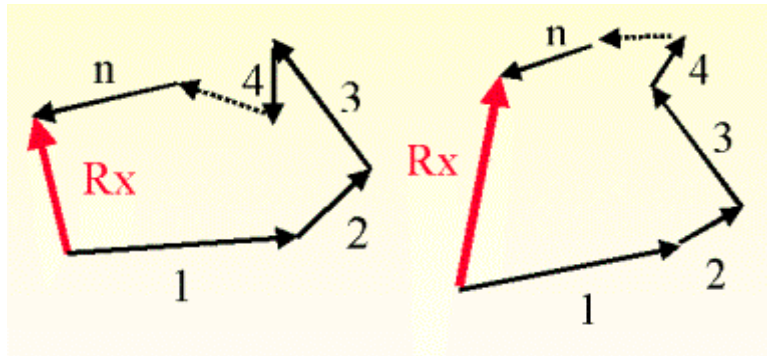
As a result, the received signal is made by several components (signal echoes), adding together with random amplitude, delay, and relative phase shift.

Observed impairments in Rx signal

Signal attenuation

Using a vectorial representation of signals, the received signal, under multipath propagation, can be viewed as the addition of multiple vectors.

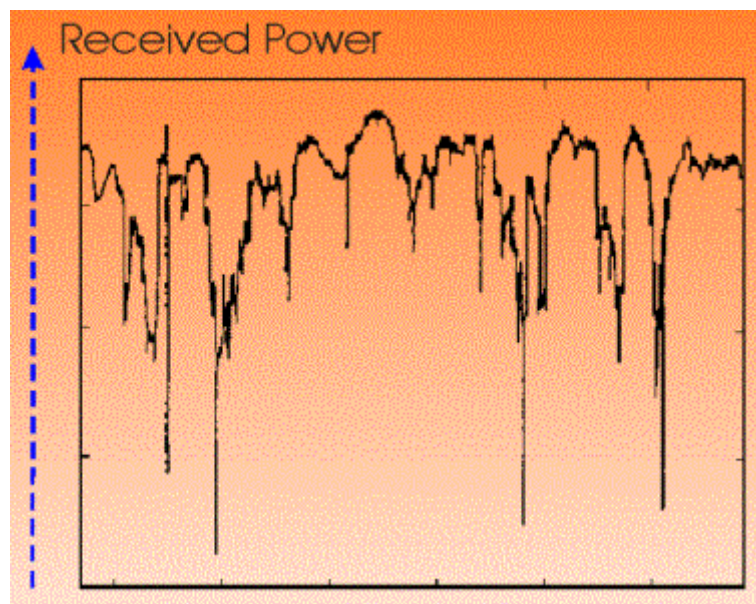
The component vectors may interfere each other, at a given time instant, in a constructive or destructive way, depending on the relative phase shifts.



Addition of multiple signal echoes, represented by vectors, at two subsequent time instant

The relative phase of component vectors depend on the difference in the path length traveled by each signal component. Note that the wavelength is of the order of centimeters and even small movements in atmospheric layers may significantly modify the path distances and the relative vector phases.

So, at different time instants, variations in the component vector phases may produce sudden variations in the resultant vector amplitude; the received signal power may be almost cancelled, for short periods (fraction of a second, or few seconds).



An example of received signal power vs. time, during a multipath propagation event

The above figure can be compared with [graphical definition](#) of received signal thresholds and margins, as given in a previous Session.

Clearly, during multipath events, the received signal power may fade below the hop threshold, so that a system outage is observed. This will be discussed in a [subsequent section](#).

Signal distortion

The phase shift δ between two vector components is computed as a function of ΔL (length difference in the paths traveled by the two rays) and of the signal wavelength λ :

$$\delta = \Delta L \cdot 360 / \lambda \text{ [deg]}$$

The above formula shows that the relative phase of component vectors depend on the signal frequency (or wavelength). The [pictures above](#) can be thought as valid for a given frequency, but slightly different phase patterns are applicable to adjacent frequencies.

This means that multipath fading is "frequency selective".

While a deep fading condition is observed at a given frequency F1, the signal at a different frequency F2 (some MHz apart) is probably received with lower attenuation.

Because of the fast variability of multipath events, this condition could be reversed in a very short time (a deep fading at frequency F2 and a higher Rx power at frequency F1).

We recall that, for undistorted transmission, the transmission channel must have a "flat" amplitude response in the whole signal bandwidth. A similar requirement applies to group-delay response.

During multipath events, it has been observed that the transmission channel cannot be considered as a "flat response" channel if the monitored bandwidth exceeds some 10 -12 MHz.

Therefore, "narrowband" signals (approximately below 10 MHz bandwidth) do not suffer the frequency selective effect of multipath propagation.

On the other hand, distortion caused by frequency selectivity represents a further impairment (in addition to signal attenuation) for "wideband" signals (approximately above 15 MHz bandwidth).

Amplitude and Group-Delay distortions produce Intersymbol Interference on digital signals, thus worsening the receiver performance for a given signal-to-noise ratio (Rx power).

Advanced - Degradation of Cross-pol discrimination

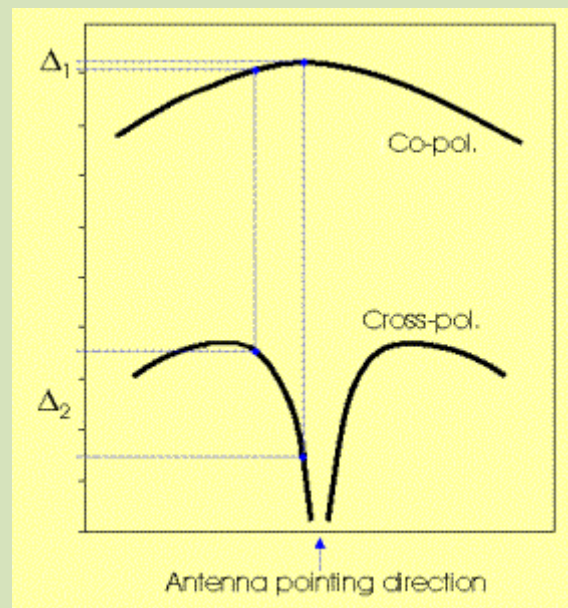
An additional impairment due to multipath fading is a degradation of the receiver cross-polar discrimination. Such discrimination is required when multiple RF channels are transmitted in a radio hop and both polarization are used ([co-channel](#) or [interleaved](#) channel arrangements).

Under non-fading conditions, the hop performance are determined by the [antenna cross-polar discrimination](#) (XPD), both at the transmitter and at the receiver.

During multipath events, as far as the signal attenuation is moderate, the cross-polar signal is usually well correlated to the co-polar one and the XPD performance is maintained.

On the other hand, when signal attenuation becomes deeper, the XPD appears to be degraded, mainly because of the antenna response to multipath components.

The mechanism can be clarified by considering the co-pol and cross-pol antenna patterns. While the co-pol pattern usually shows a rather flat maximum in the pointing direction, the cross-pol pattern has a very narrow minimum in the same direction.



Antenna response to two rays, with slightly different arrival angles: the two co-pol components are almost equal, while the difference between the cross-pol components is large (Δ_2).

The two co-pol components may almost cancel (if with opposite phase), while the dominant cross-pol component is large in any case. So a significant degradation may affect the overall XPD.

A second mechanism may be involved in the XPD degradation during multipath events, when some multipath components are produced by reflection or terrain scattering. In that case, the signal polarization of the reflected or scattered signal is rotated (in some measure) and the cross-pol signal is increased.

Performance prediction models usually assume that, as far as the signal attenuation is within some 10-15 dB, the XPD is determined by the antenna measured performance. On the other hand, for deeper fades, some XPD degradation is expected (up to 1 dB additional degradation for 1 dB additional signal attenuation).

Modeling multipath activity

Multipath events are observed with daily and seasonal cycles, when suitable refractive gradient profiles are more often observed. A multipath activity period can last tens of minutes, or even one or several hours.

A prediction model of multipath activity is implemented by correlating significant radio link and environmental parameters with statistical observation of multipath events.

Radio and environmental parameters

Radio link parameters which have been recognized as affecting multipath events are:

- Working frequency;
- Path length;
- Path inclination.

Environmental conditions which are likely to produce multipath events are:

- flat terrain;
- strong evaporation (high temperature and humidity);
- absence of wind.

It is often useful to identify climatic regions with specific characteristics, so that multipath activity can, in some measure, be correlated with regional parameters. Particularly in tropical climates, long multipath events can be observed.

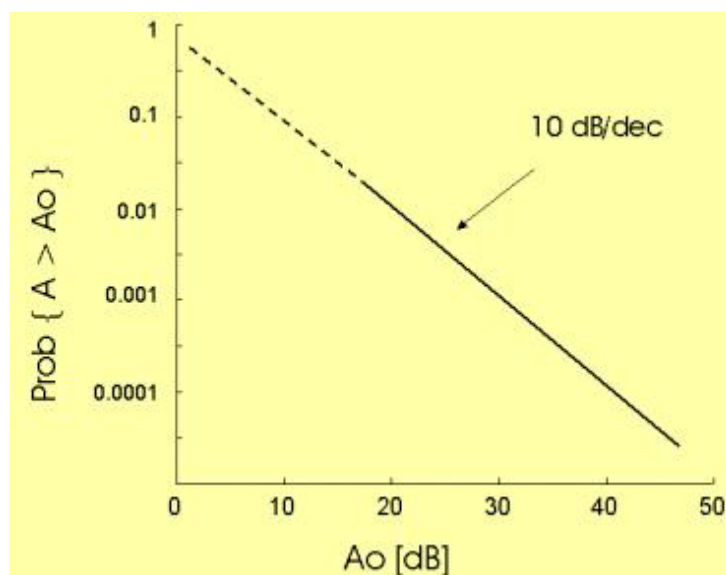
Statistical observation of multipath events

By monitoring a radio hop during multipath events, a number of recordings, similar to the [above figure](#), can be collected. This enables to build up statistical data about the time periods with fade depth below given thresholds.

A large amount of similar experiments have shown that fade depth statistics are well approximated by a Rayleigh distribution (at least for fade depth greater than about 15 dB). According to that distribution, the probability that the signal fade depth A (in dB) is deeper than a given value A_0 is given by :

$$\text{Prob}\{A > A_0\} = P_0 \cdot 10^{(-A_0/10)}$$

where P_0 is called "multipath occurrence factor". (To be more precise, this is the Rayleigh "asymptotic" trend, derived for low probability and deep fade levels).



Note that, if the reference fade depth A_0 increases 10 dB, then the corresponding probability is lower by a factor 10 (the diagram slope is 10 dB / decade).

This [experimental result](#) is in good agreement with mathematical analysis, applied to the random vector model, previously mentioned. It can be shown that, if we add a large number of vectors, with random amplitudes and phases, then the resultant vector amplitude is a random variable with Rayleigh distribution.

Multipath Occurrence Factor

The Rayleigh model for multipath fade depth is described by a single parameter P_0 .

We can imagine to collect fade depth statistics on a given radio hop in different time periods, or on radio hops with different length, working frequency, and/or in different climates. We expect that, in some measure, the experimental results approximate the Rayleigh formula given above, even if a different P_0 value will apply in each case. So, the P_0 parameter gives a measure of the "multipath activity" on a given hop and within a given time period.

The above example suggests an experimental means to estimate the P_0 factor when a radio hop is already working. However, the radio engineer needs prediction tools to estimate P_0 while a radio hop is at the design stage.

Several empirical formulas have been proposed, giving P_0 as a function of radio hop parameters and of environmental conditions. The relevant factors are those mentioned in a [previous section](#).

Most of these formulas have the following structure :

$$P_0 = C \cdot Q \cdot F^\alpha \cdot D^\beta$$

where C (geoclimatic coefficient), Q (terrain profile coefficient), α (frequency exponent), and β (path length exponent) are empirical parameters. They are usually estimated by processing large amounts of experimental data, or can derive from more complex formulas, again related to the results of field measurements.

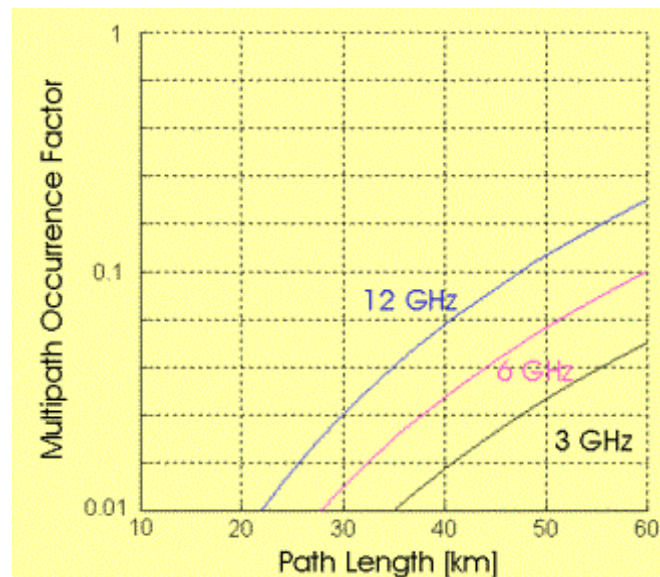
Generally, P_0 is proportional to frequency (the α exponent is equal, or close, to 1), while the β exponent is in the range 3 - 3.6 (the multipath occurrence increases about ten times when the hop length is doubled).

Probably, the most popular model for P_0 prediction is the Bell Labs formula (reported in papers by W.T. Barnett and A. Vigants, in the early 70's). The [general formula](#) mentioned above is applied (frequency in GHz, distance in km), with the following parameters:

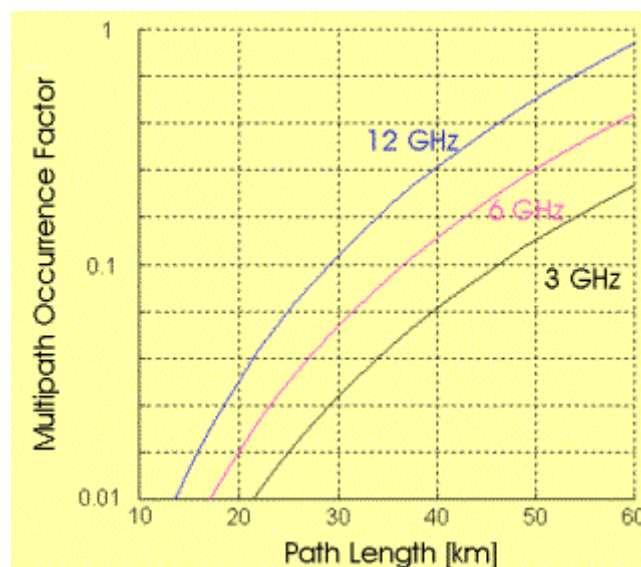
- $\alpha = 1$;

- $\beta = 3$;
- $C = 1 \cdot 10^{-5}$ for dry mountainous regions;
- $C = 2.1 \cdot 10^{-5}$ for continental temperate regions;
- $C = 3.1 \cdot 10^{-5}$ for maritime temperate regions;
- $C = 4.1 \cdot 10^{-5}$ for maritime sub-tropical, high humidity and temperature regions;
- $Q = 1 / \sigma^{1.3}$
- σ = profile roughness, measured in meters as the standard deviation of terrain elevations at 1 km intervals (in any case, σ must be in the range 6 m to 42 m).

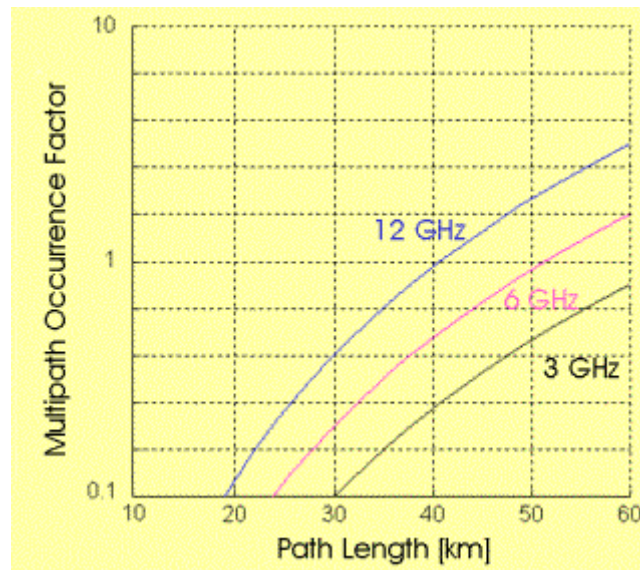
Examples of the Barnett-Vigants model are given below.



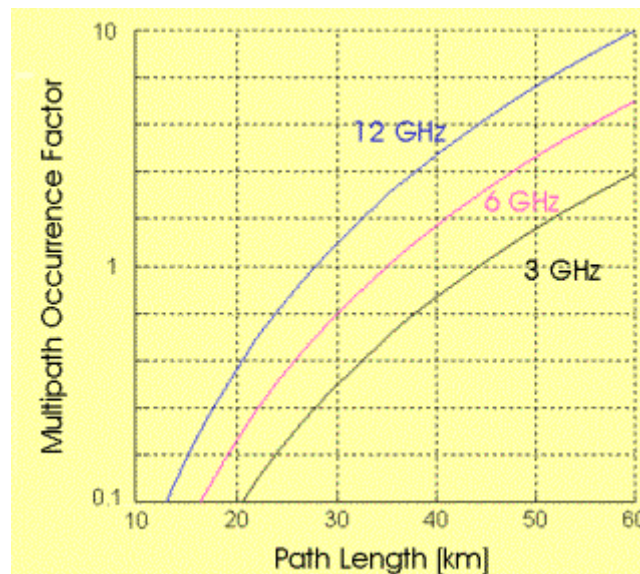
Application of the Barnett-Vigants model: High dry mountainous regions; high roughness terrain ($\sigma = 42$ m)



Application of the Barnett-Vigants model: Temperate continental regions; average rolling terrain ($\sigma = 24$ m)



Application of the Barnett-Vigants model: Temperate maritime regions; low roughness terrain ($\sigma = 12$ m)



Application of the Barnett-Vigants model: Sub-tropical, high humidity regions; flat terrain ($\sigma = 6$ m)

An alternative model is proposed by ITU-R Rec. P.530-9. The model structure is slightly different and more complex with respect to the general formula mentioned above. This model has been frequently revised in recent ITU-R meetings and probably it is not yet at a final version.

Advanced - ITU-R Multipath occurrence model

ITU-R Rec. P.530-9 (released June 2001) gives a model for the prediction of the Multipath Occurrence Factor P_0 .

The model provides two different formulas, to be applied for detailed link design or for preliminary planning, respectively. The main difference in the two approaches is that the detailed design makes use of data on terrain roughness around the radio path.

(Note : Rec. P.530 gives the Rayleigh formula in %; a 0.01 factor is added in the P_0 expressions given below to take account of this).

Detailed link design :

$$P_0 = 0.01 \cdot K \cdot D^{3.2} \cdot \left(1 + \left|\varepsilon_p\right|\right)^{-0.97} \cdot 10^{0.032F - 0.00085HL}$$

where : K (= geoclimatic factor) is given by :

$$K = 10^{-3.9 - 0.003dN1} \cdot s_A^{0.42}$$

ε_p = path inclination in milliradians;

HL = elevation of the lower antenna in meters;

dN1 = refractivity gradient in the lowest 65 m of the atmosphere, not exceeded for 1% of an average year;

s_A = area roughness around the radio path.

The refractivity gradient dN1 is provided on a 1.5° grid in latitude and longitude in ITU-R Rec. P.453.

The area roughness is defined as the standard deviation of terrain heights (m) within a 110 km x 110 km area with a 30 s resolution.

Preliminary planning :

$$P_0 = 0.01 \cdot K \cdot D^{3.0} \cdot \left(1 + \left|\varepsilon_p\right|\right)^{-1.2} \cdot 10^{0.033F - 0.001HL}$$

where : K (= geoclimatic factor) is given by :

$$K = 10^{-4.2 - 0.0029dN1}$$

and the other symbols are already defined above.

Comment

The ITU-R model derives from the processing of a significant amount of P_0 estimates, at several frequencies (up to 37 GHz) and with various path lengths in different climatic environments.

The mathematical approach is mainly based on minimizing the standard deviation between empirical data and prediction formulas by means of multiple regressions. The positive aspect is that the model is well related to observations in real links. It is stated that the overall standard deviations of error using the proposed models is of the order of 5 dB (including the contribution from year-to-year variability).

On the other hand, a physical model underlying formula structure and parameter choice is not clearly defined, so that it appears that the proposed approach could be revised on the basis of a new experimental database, as already happened in recent years.

Performance prediction

In a [previous Session](#), general concepts about fade margin and outage prediction have been briefly discussed. In particular, it was found convenient to distinguish between two outage conditions:

- when the outage is only caused by insufficient Rx power (received signal level below the hop threshold);
- when distortion in the Rx signal is expected to contribute to the outage, even when the Rx power is still above the hop threshold.

In the context of multipath propagation, the first condition applies to "narrowband" signals, since it is assumed that they do not suffer any distortion during multipath events. On the other hand, the second condition applies to "wideband" signals, which may be severely distorted by frequency selective multipath.

Outage prediction in Narrowband systems

Outage events are observed when the Rx power is below the hop threshold.

Taking account of the [multipath fading Rayleigh distribution](#), the outage probability P_{OUT} , can be predicted as :

$$\begin{aligned} P_{OUT} &= \text{Prob}\{\text{Rx Power} < \text{Hop Threshold}\} = \\ &= \text{Prob}\{A > FM\} = P_0 \cdot 10^{(-FM/10)} \end{aligned}$$

where A is the signal attenuation caused by multipath propagation, FM is the hop Fade Margin, and P_0 is the [multipath occurrence factor](#).

The outage time T_{OUT} during a given observation time T_0 (typically, one month), is finally given as $T_{OUT} = T_0 P_{OUT}$.

In conclusion, two parameters are required for outage time prediction:

- the hop Fade Margin, given by the [Link Budget](#) computation;
- the multipath occurrence factor P_0 , given by some model for multipath activity, as the [Barnett-Vigants](#) one, presented above.

In this context, the Fade Margin is often referred as the Flat Fade Margin, since it is used to compensate for non-selective (flat) attenuation.

Advanced - Outage prediction in Wideband systems

The prediction of Outage Time in Wideband systems takes account that outage events may be caused by the combined effect of signal attenuation and distortion. As a result, the outage condition may be observed even if the Rx power is still above the receiver power threshold.

Reference will be made to the prediction model reported in ITU-R Rec. P.530-9. Using a simplified approach, the model deals separately with the two impairments (signal attenuation and distortion), so that the general formula for outage probability prediction is :

$$P_{OUT} = P_{NS} + P_S$$

where P_{NS} is the outage probability due to signal attenuation (non-selective outage component), which is given by the same [outage formula derived for narrowband systems](#), while P_S is the outage probability due to signal distortion (selective outage).

The selective component P_S depends on the receiver sensitivity to signal distortion. The [Signature Measurement](#) is the tool used to characterize a radio equipment under this aspect. P_S is given by :

$$P_S = 2.15 \cdot \eta \cdot \left[W_M \cdot 10^{-B_d/20} \cdot \frac{\tau_m^2}{\tau_r} + W_{NM} \cdot 10^{-B_{NM}/20} \cdot \frac{\tau_m^2}{\tau_r} \right]$$

where :

$$\eta = 1 - \exp \left[-0.2 \cdot P_0^{0.75} \right]$$

is the Multipath Activity (directly related to the Multipath Occurrence Factor P_0);

$$\tau_m = 0.7 \cdot [D/50]^{1.3}$$

is the mean time delay [ns] of multipath echo components, which is a function of the hop length D (in km);

W is the signature width [GHz];

B is the signature depth [dB];

τ_r is the echo delay in the signature measurement.

Subscript "M" indicates that the signature was measured with a Minimum -Phase channel, while subscript "NM" refers to a Non-Minimum-Phase channel.

Advanced - Outage contribution from X-pol interference

Since multipath events have an impact in reducing discrimination between cross-polarized signals, multipath outage is increased by the effect of cross-polar interference.

The Rec. P.530-9 prediction model assumes that cross-polar interference contributes to the outage probability with an additive term P_{XP} .

$$P_{XP} = P_0 \cdot 10^{0.1[XP D + S + Q - (C/I)_0]}$$

where :

$(C/I)_0$ is the threshold Carrier-to-Interference ratio;

XP D is the minimum cross-pol discrimination of the Tx and Rx antennas;

$$Q = 1 - \text{Log}_{10}[0.7 \cdot \eta / P_0]$$

is an empirical parameter, where P_0 is the multipath occurrence factor and η is the multipath activity, previously defined.

Notes :

- 1) If $XP D > 35$ dB, then put $XP D = 35$ dB in the P_{XP} formula;
- 2) If a Cross-Pol Interference Canceller (XPIC) is used, then the threshold C/I must be reduced by an amount equal to the XPIC gain;
- 3) if two separate antennas are used to transmit the cross-polarized signals, then the Q definition is revised, by replacing the 0.7 factor with the K factor below:

$$K = 1 - 0.3 \cdot \exp\left[-4 \cdot 10^{-6} \left(\frac{s}{\lambda}\right)\right]$$

(s = vertical antenna spacing, λ = signal wavelength).

Countermeasures

Several techniques have been devised to reduce the impairments caused by multipath propagation.

Space Diversity

As with [reflection paths](#), two Rx antennas, with a suitable vertical spacing, receive the multipath component signals with different phase patterns.

So, in a well arranged space diversity configuration, the Rx signals at the two antennas will exhibit a low correlation and the probability of deep fading at the same time can be significantly lowered. Typical spacing is of the order of 150 - 200 wavelengths.

A diversity improvement factor I_{SD} is defined as :

$$I_{SD}(A_0) = \frac{\text{Prob}\{A_1 > A_0\}}{\text{Prob}\{A_1 > A_0, A_2 > A_0\}}$$

where A_1 and A_2 are the attenuations at the two diversity receivers, A_0 is a reference attenuation and $\text{Prob}\{X, Y\}$ means probability that events X and Y are true at the same instant (joint probability).

The [Barnett-Vigants model](#) is extended to space diversity reception, giving :

$$I_{SD}(A_0) = 0.0012 \cdot \frac{F}{D} \cdot S^2 \cdot 10^{(A_0 - V/10)}$$

where F is the working frequency in GHz, D the path length in km, S the vertical spacing in m, and V is the difference of the two antenna gains in dB. Note that the improvement factor is a function of the reference attenuation A_0 , so at different fade levels a different improvement is predicted.

The Outage Time prediction, for a Narrowband system, is derived from the [Single Rx prediction](#) and the definition of [diversity improvement](#) :

$$\begin{aligned} (T_{OUT})_{SpaceDiv} &= T_0 \cdot \text{Prob}\{A_1 > FM, A_2 > FM\} = \\ &= T_0 \cdot \frac{\text{Prob}\{A_1 > FM\}}{I_{SD}(FM)} = \frac{(T_{OUT})_{Single}}{I_{SD}(FM)} \end{aligned}$$

Advanced - ITU-R model for Space Diversity improvement

An alternative formula to predict the space diversity improvement is given by ITU-R Rec. P.530-9:

$$\begin{aligned} I_{SD}(A_0) &= \\ &= \left[1 - \exp \left(- 3.3 \cdot 10^{-4} \cdot S^{0.87} \cdot F^{-0.12} \cdot D^{0.48} \cdot P_0^{-1.04} \right) \right] \cdot 10^{(A_0 - V/10)} \end{aligned}$$

The Improvement factor is a function of the reference attenuation A_0 . F is the working frequency in GHz, D the path length in km, S the vertical spacing in m, P_0 is the Multipath Occurrence Factor and V is the difference of the two antenna gains in dB (if any).

(Note : coefficients have been revised in comparison with ITU-R formula because Rec. P.530 gives the Multipath Occurrence factor in %).

1+1 Frequency Diversity

Again, we refer to [general concepts on diversity techniques](#).

In this case, we exploit the [frequency selective](#) nature of multipath fading, so that two RF channels with suitable frequency spacing exhibit the low correlation property, which guarantees a low probability of deep fading in the two channels at the same time.

Since a protection channel is often required in multi-channel radio-relay systems in case of equipment failure, it can be convenient that the same protection channel be used also as a frequency diversity countermeasure to multipath fading.

For effective multipath protection, fast quality detector and switching circuits are required.

In a 1+1 configuration, one working channel is continuously protected by one spare channel. Similarly to [Space diversity](#), a Frequency Diversity Improvement Factor I_{FD} can be defined. According to the Barnett-Vigants model, also applied in ITU-R Rec. P.530, it can be estimated as :

$$I_{FD}(A_0) = \frac{80}{F \cdot D} \cdot \frac{\Delta F}{F} \cdot 10^{(A_0/10)}$$

where F is the average working frequency and ΔF is the channel spacing (both in GHz), D is the path length in km. Also in this case, the improvement factor is a function of the reference attenuation A_0 (in dB).

Advanced - N + 1 Frequency Diversity

The frequency diversity arrangement can be extended from the 1+1 configuration, as assumed above, to N+1 configurations, where one RF channel is used as a protection for N working channels

In N+1 systems it is expected that the frequency diversity effectiveness is reduced in some measure.

If, in the unprotected condition, M channels are in the outage state, then using frequency protection the number of outage channels is reduced to M-1. A fairly complex probability and combinatorial problem must be solved to estimate the outage time reduction given by N+1 frequency diversity.

With good approximation, a simplified solution is obtained by defining an "equivalent channel spacing". By this approach, the Frequency Diversity improvement in N+1 systems with channel spacing ΔF is equal to the improvement in an "equivalent" 1+1 diversity system with channel spacing ΔF_{EQ} given by:

$$\Delta F_{EQ} = \Delta F \cdot \frac{N}{\sum_{j=1}^N \frac{N+1-j}{j}}$$

So, we can use again the previous [\(1+1\) improvement formula](#), with ΔF_{EQ} instead of ΔF .

Advanced - Outage in Wideband systems with Diversity

In rather general terms, it can be stated that the outage probability in a diversity system ($P_{OUT,DIV}$) is related to the outage probability with single reception ($P_{OUT,SINGLE}$) through the formula :

$$P_{OUT,DIV} = \frac{(P_{OUT,SINGLE})^2}{\eta \cdot (1 - k^2)}$$

where η is the (previously defined) [multipath activity](#) (that is the fraction of time with multipath events) and k is the correlation factor between the two diversity signals.

In the case of the non-selective outage probability, the Diversity Improvement $I_{DIV} = (P_{OUT,SINGLE} / P_{OUT,DIV})$ is given by empirical formulas, for both [Space](#) and [Frequency Diversity](#). Then, the above formula can be reversed to derive the non-selective correlation factor k_{NS} :

$$\left[k_{NS}^2 \right]_{SD} = 1 - \frac{I_{SD} \cdot P_{OUT,NS}}{\eta} \left[k_{NS}^2 \right]_{FD} = 1 - \frac{I_{FD} \cdot P_{OUT,NS}}{\eta}$$

On the other hand, the selective correlation factor k_s is given by Rec. P.530-9 as a function of k_{NS} ,

Once the (non-selective and selective) correlation factors are known, the outage probabilities can be computed using the [general formula](#) reported above, for both the non-selective outage component ($P_{NS,DIV}$) and the selective one ($P_{S,DIV}$).

Finally, the two outage components are combined to give the overall outage probability:

$$P_{OUT,DIV} = \left[P_{NS,DIV}^{0.75} + P_{S,DIV}^{0.75} \right]^{4/3}$$

Note : The outage prediction model reported by ITU-R Rec. P.530-9 gives different formulas to combine the non-selective and selective outage components in the single and diversity conditions.

Advanced - Adaptive equalizers

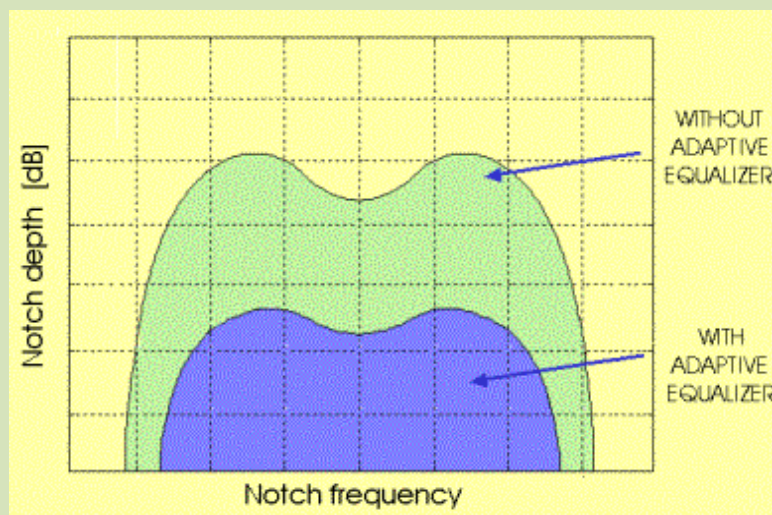
Adaptive equalization is part of the demodulation process. The equalizer is implemented as a self-adjusting circuit (at the IF or baseband stage), which is able to partially compensate for multipath distortion in wideband digital systems.

The objective is to reduce the selective outage component, so that (with an ideal equalizer) outage should be observed only when the received power fades below the Rx threshold.

The IF equalizer is usually described in the frequency domain, as a circuit whose transfer function is complementary to the multipath channel transfer function. The overall transfer function (transmission channel plus equalizer) should approximate an ideal non-distorting channel.

The BB equalizer is usually described in the time domain, as a transversal filter (or decision feedback filter), which cancels undesired tails in the transmission channel impulse response, so reducing intersymbol interference. In some radio equipment, the BB equalizer and the Cross-pol Interference Canceller (XPIC) are implemented in a single circuit.

The receiver signature gives a measure of the effectiveness of an adaptive equalizer. By comparing the signature with and without equalizer, the improvement (outage reduction) given by the equalizer can be estimated (see the selective outage prediction formula, based on signature parameters).



Equipment signatures without and with an adaptive equalizer.

This concludes Section 5 of the PPRLE. Please proceed to Herald Lab Exercise 5.

End of Section #5

SECTION 6 – RAIN ATTENUATION

Summary

In this Session we first discuss the interaction of an EM wave with molecules encountered throughout the propagation path in the atmosphere. This leads to an estimate of rain specific attenuation, as a function of rain intensity, signal frequency and polarization. Statistical data on rain intensity are considered, as required by the ITU-R rain attenuation model, which is presented as the basic tool to predict rain unavailability in any region in the world, at frequencies up to about 40 GHz.

EM wave interaction with atmosphere

Even if this Session is mainly devoted to rain effects, we first consider, in more general terms, the interaction of EM waves with molecules and particles encountered throughout the propagation path in the atmosphere.

Two effects are most significant:

- absorption: EM energy transferred to the impacted molecules and converted into heat;
- scattering: EM energy re-irradiated away from the propagation direction it had before impact.

Both effects are mainly affected by:

- Molecule / particle dimensions, relative to the wavelength of the EM radiation;
- Electrical properties of the involved molecules.

We consider the effect of the atmosphere in the absence of rain and the attenuation due to raincells.

Phenomena related to other hydrometeors (snow, ice, fog, hail) and even to dust storms will not be discussed here (ITU-R Rec. P-840 gives some indication about the effect of thick clouds and fog).

Water vapour and Oxygen attenuation in clear air

In the frequency range up to about 40 GHz, the atmospheric molecules which interacts with EM waves are water (in the form of water vapour) and, more marginally, oxygen.

A water vapour absorption peak is observed at 22.2 GHz, while the first oxygen absorption peak is at about 60 GHz. Other absorption peaks, for both water vapour and oxygen, are at higher frequencies.

The maximum attenuation due to water vapour (γ_{wv}), at 22.2 GHz, is given by (according to ITU-R Rec. P-676) :

$$\gamma_{wv}(dB/km) = p \cdot (2.34 \cdot 10^{-2} + 1.035 \cdot 10^{-4} \cdot p)$$

where p is the vapour density in g/m^3 , the atmospheric pressure is 1013 hPa and the temperature is 15°C.

This gives a 0.30 dB/km attenuation at the water vapour saturation level (about 12 g/m^3 at 15 °C) and 0.18 dB/km at a lower vapour density of 7.5 g/m^3 .

On the other hand, the specific attenuation due to oxygen exceeds 1 dB/km in the frequency range 52 to 68 GHz; the maximum attenuation, at 60 GHz, is about 16 dB/km, while at 40 GHz it is below 0.1 dB/km.

For radio hops up to about 40 GHz, the conclusion is that the power loss caused by atmospheric absorption is usually not significant. In most cases it can be neglected in the Link Budget, also considering that the hop length is anyway limited by rain attenuation.

Rain attenuation

An EM wave, traveling in a given direction through a raincell, loses part of its power in that direction, as a result of absorption and scattering effects.

In the impact with a raindrop, the total power lost depends on the "drop cross section", which is given by the sum of a scattering cross section and an absorption cross section.

The drop cross section is a function of the drop radius and of the signal wavelength.

By integrating the power lost in the impact with a single raindrop to all the raindrops in a given volume (raincell), the total loss produced within that raincell can be estimated.

To do this, suitable statistical models are needed to relate the number of raindrops in a raincell and their size distribution to the rain intensity. Such models have been tuned on the basis of a large amount of experimental data, coming from different regions in the world.

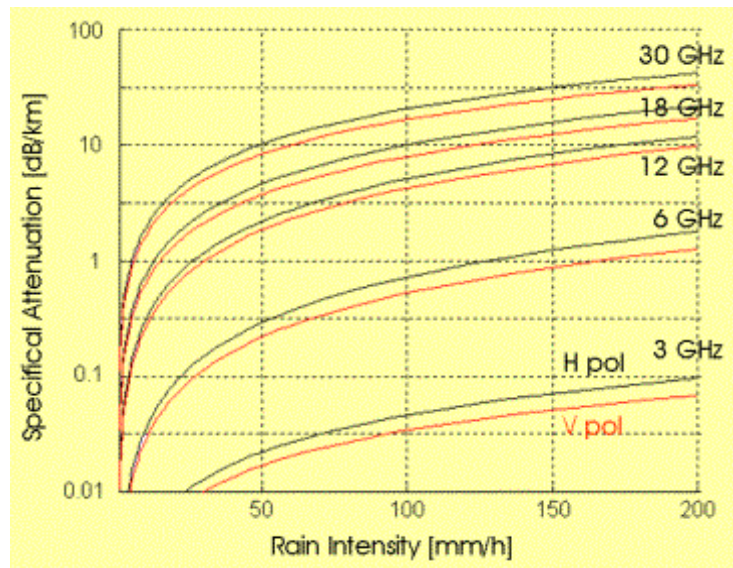
As a result, the specific rain attenuation γ (dB/km) can be expressed, as a function of the rain rate R (in mm/h), by the following exponential formula:

$$\gamma = k \cdot R^{\alpha}$$

where the parameters k and α are functions of the signal wavelength and polarization.

ITU-R Rec. P-838 gives a table with the k and α values, for Vertical and Horizontal polarizations, in the frequency range 1 to 400 GHz. Formulas are given for the case of any linear or circular polarization.

Examples of specific rain attenuation as a function of rain rate, are given in the figure below; note that the increase in specific attenuation is about 100 times, when passing from 3 to 12 GHz. Moreover, the Vertical polarization is significantly less attenuated than Horizontal polarization, at the same frequency.



Attenuation vs. rain intensity, for different signal frequencies, vertical (red) and horizontal (black) polarizations

Advanced - Other rain impairments

EM wave depolarization - An additional effect must be considered when a linearly polarized EM wave travels through a raincell: a rotation of the polarization plane, so that an orthogonally polarized component can be observed at the output of the cell.

The de-polarization effect is related to the raindrop shape and to the dropping angle (in most cases, not perfectly vertical).

It is possible to establish a statistical relation between rain attenuation and depolarization effect. For a given probability P , we define the "equi-probable" levels in co-polar attenuation (CPA_P) and cross-polar discrimination (XPD_P) as:

$$\text{Prob}\{XPD < XPD_P\} = \text{Prob}\{CPA > CPA_P\} = P$$

XPD_P can be predicted from CPA_P (that is when the CPA cumulative distribution is known) as:

$$XPD_P = U - V \cdot \text{Log}_{10}[CPA_P]$$

where : $U = 15 + 30 \cdot \text{Log}_{10}(f)$

$$V = 12.8 \cdot f^{0.19} \quad 8 \leq f \leq 20 \text{ GHz}$$

$$V = 22.6 \quad 20 < f \leq 35 \text{ GHz}$$

Interference due to wave scattering - A raincell may become a potential source of interference to other radio systems, since part of the EM energy which impacts the cell is scattered in multiple directions. The propagation model to be applied in such conditions is described by ITU-R Rec. P.452-10.

It is rather unlikely that a P-P link may produce a significant interference effect to another P-P link, through raincell scattering. The TX power level is usually at (or below) 1 W and the cell scattering works almost like an omnidirectional radiator, so a low power density is associated with the scattered signal.

On the other hand, high power radio transmitters, in particular large earth stations for satellite communications, have the potential for producing a not negligible interference through raincell scattering. Detailed procedures are recommended by ITU-R documents to take account of this, when the satellite system operates in frequency bands shared with terrestrial systems.

Worldwide rain intensity statistics

An important input to any rain attenuation model is the expected rain activity in the region where the radio hop will operate, as derived from long-term statistics.

More specifically, it was found useful to refer to the low-probability tails of rain statistics, since we are mainly interested in rare events with very heavy rainfall.

The rain rate exceeded for 0.01% of the time is the significant parameter, useful to characterize the rainfall activity in a given region.

If possible, this rain rate should be derived from reliable statistical data about the local rain events. When local data are not available, the procedure recommended by ITU-R can be used.

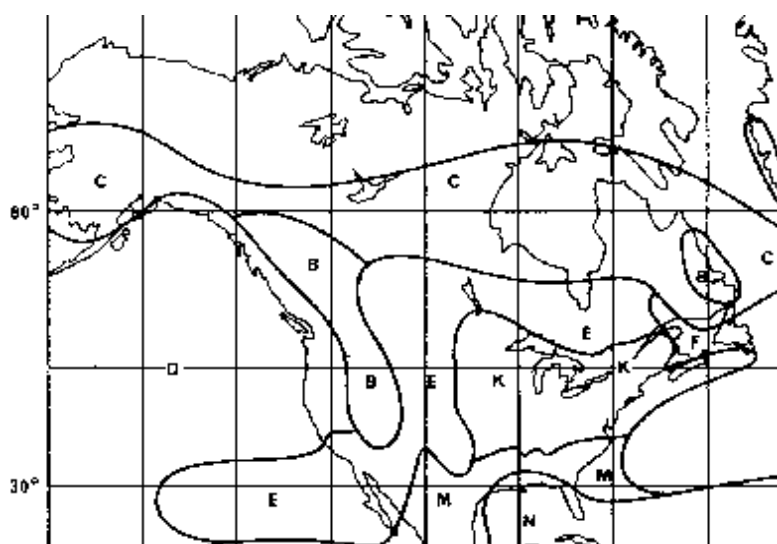
In the last release of Rec. P-837 a new approach is reported to estimate the rain rate exceeded for any percentage of time, in any part of the world. This is based on data files (available from the ITU website), derived from 15 years of data of the European Centre of Medium-range Weather Forecast (ECMWF). They cover all the world, with latitude and longitude grids in 1.5° steps. A suitable interpolation procedure is recommended.

To give an approximate information about the rain rates used in rain attenuation predictions, the previous ITU-R approach is reported, which was based on world maps with "rain regions".

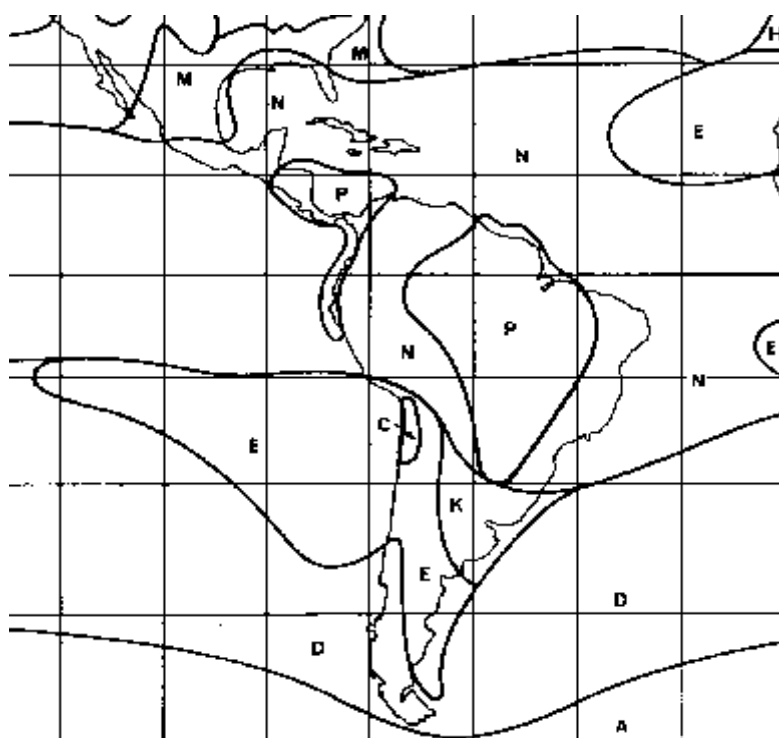
Each region was labeled with a letter; in the table below, each letter is associated with the corresponding rain rate (in mm/h) exceeded for 0.01% of the time :

A	8	D	19	G	30	K	42	N	95
B	12	E	22	H	32	L	60	P	145
C	15	F	28	J	35	M	63	Q	115

The world maps are shown below.



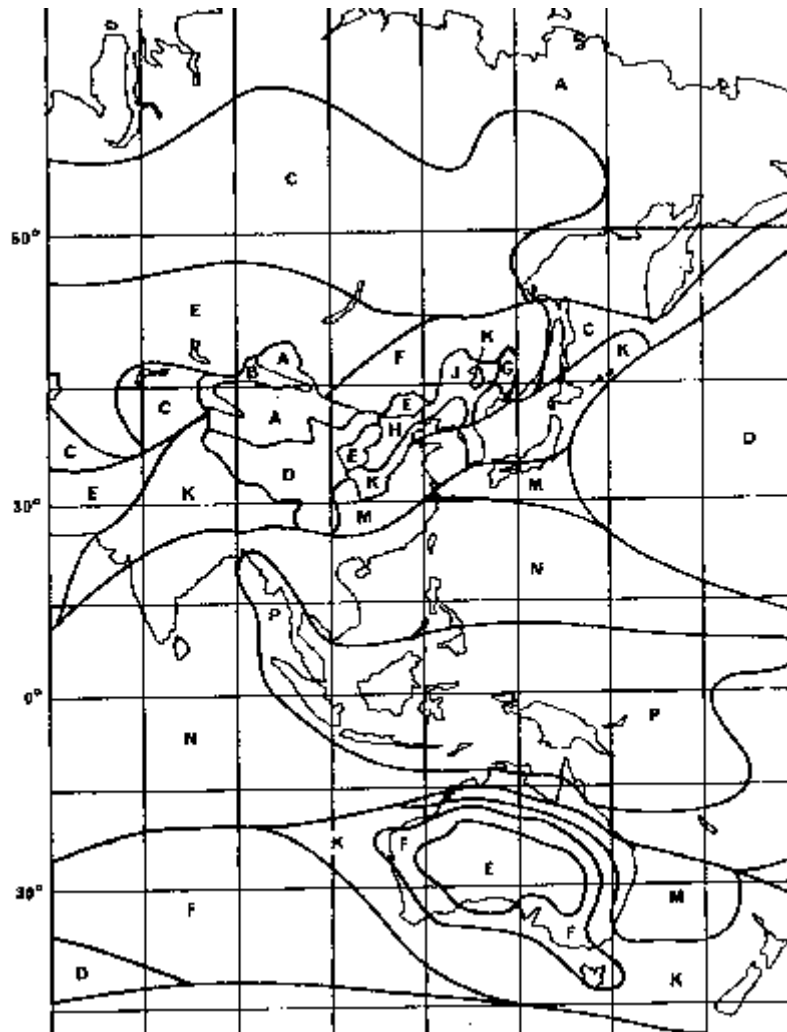
ITU-R Rain regions, North America (from ITU-R Rec. P-837-1 Fig.1, by ITU permission)



ITU-R Rain regions, Centre and South America (from ITU-R Rec. P-837-1 Fig.1, by ITU permission)



ITU-R Rain regions, Europe, Africa and Middle East(from ITU-R Rec. P-837-1 Fig.2, by ITU permission)



ITU-R Rain regions, Asia and Oceania (from ITU-R Rec. P-837-1 Fig.3, by ITU permission)

ITU-R rain attenuation model

Rain intensity model

In order to apply raincell models to the estimate of rain attenuation in a radio hop, it is necessary to consider how the raincell size compare to the hop length.

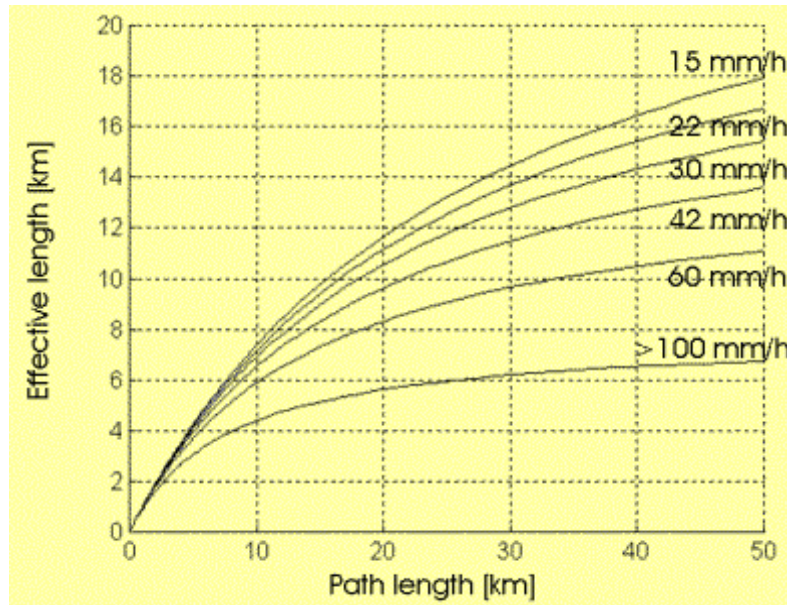
While in very short hops (below some 2 - 3 km) the whole length may be affected by rainfall, in longer hops a raincell occupies only a portion of the whole distance.

ITU-R Rec. P-530 defines an "effective hop length" D_{EFF} , in order to take account of raincell size :

$$D_{EFF} = \frac{D}{1 + D / [35 \exp(-0.015R)]} \quad R < 100 \text{ mm/h}$$

$$D_{EFF} = \frac{D}{1 + 0.128 \cdot D} \quad R \geq 100 \text{ mm/h}$$

Note that the effective length is a function of the local rain rate R (in mm/h). As shown in the diagram below, the effective length is more compressed with high rain rates (a raincell with high rain rate is expected to occupy a smaller area). On the other hand, the effective length is close to the real length as far as the latter is approximately below 4 km.



Conversion from real path length to effective length D_{EFF} for various rain rate values

ITU-R Rec. P-530 gives a step-by-step procedure to estimate the time percentage that rain attenuation exceeds a given threshold on a radio hop.

Input parameters are the hop length, the signal frequency and polarization, and the operating region. The recommended procedure is as follows:

- Estimate of the local rain rate R for 0.01% of time. This should derive from long-term statistical data collected in the specific zone; otherwise, [ITU-R data](#) can be used, as indicated in the previous section.
- Application of the [specific loss \(\$\gamma\$ \) formula](#), given the rain rate R , the signal frequency F and polarization (H or V).
- Reduction of the hop length to the Effective Length D_{EFF} (km), according to the [above formula](#).
- Computation of Rain Attenuation exceeded for 0.01% of time :

$$A_{0.01} = \gamma \cdot D_{EFF}$$

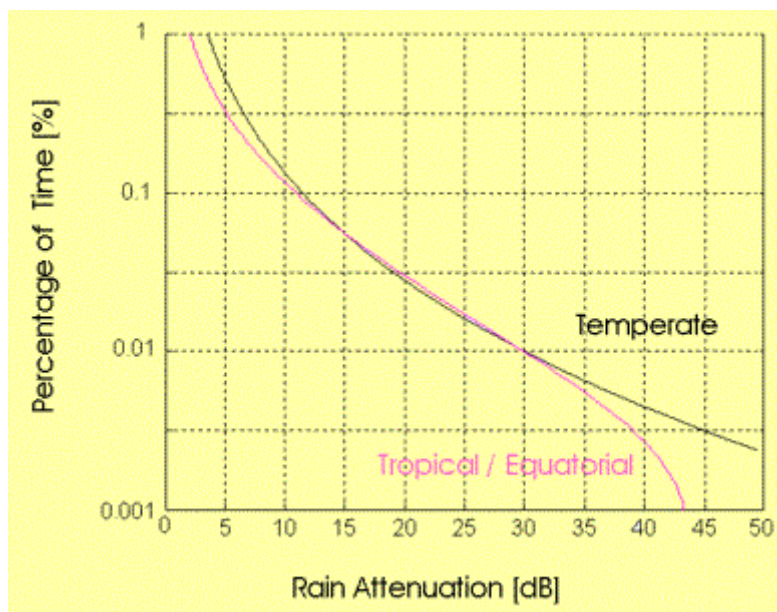
- Extrapolation to other time percentages p , in the range from 1% to 0.001% :

$$A_p = A_{0.01} \cdot 0.12 \cdot p^{-(0.546+0.043 \log_{10} p)}$$

for temperate climate (latitude greater than 30°, North or South), while for tropical / equatorial climate (latitude below 30°) :

$$A_p = A_{0.01} \cdot 0.07 \cdot p^{-(0.855+0.139 \log_{10} p)}$$

An example is given below, where $A_{0.01}$ has been assumed to be 30 dB. Note that the abscissa gives the attenuation exceeded for the corresponding time percentage.



Percentage of time vs. Rain attenuation, assuming $A_{0.01} = 30$ dB, in different climates

The ITU-R prediction method is considered to be valid for frequencies up to 40 GHz and hop lengths up to 60 km.

Advanced - Frequency / polarization scaling model

An alternative model proposed by ITU-R (Rec. P.530) can be applied when experimental results are available about rain attenuation on the same hop, measured at a different frequency and/or polarization.

In that case, we need to scale the measured result to the frequency and/or polarization used in the project of interest.

The following empirical formula can be used to estimate rain attenuation A_2 at frequency F_2 , for a given time percentage, when long-term experimental statistics at frequency F_1 predict attenuation A_1 for the same time percentage (frequency in GHz, attenuation in dB):

$$A_2 = A_1 \cdot [\Phi_2 / \Phi_1]^{1-H(\Phi_1, \Phi_2, A)}$$

where $H(\Phi_1, \Phi_2, A) = 1.12 \cdot 10^{-3} \cdot [\Phi_2 / \Phi_1]^{0.5} \cdot [\Phi_1 \cdot A]^{0.55}$

$$\Phi(F) = \frac{F^2}{1 + 10^{-4} \cdot F^2}$$

Similarly, when long-term experimental statistics on a given polarization at frequency F predict attenuation A for a given time percentage, then the attenuation on the orthogonal polarization, at the same frequency and for the same time percentage can be estimated as :

$$A_V = \frac{300 \cdot A_H}{335 + A_H} \quad A_H = \frac{335 \cdot A_V}{300 - A_V}$$

Rain unavailability prediction

For a given radio hop, the attenuation due to rain for 0.01% of the time can be estimated, according to the ITU-R procedure, as a function of the local rain rate, of the hop length, and of the signal frequency and polarization.

To predict the hop unavailability caused by rain, it is convenient to reverse the [formulas given above](#), in order to get the time percentage p as a function of the attenuation A exceeded for p% (note anyway the 0.001% to 1% application range) :

$$p(A) = 10^{Q(A)}$$

where :

$$Q(A) = \frac{-0.546 + \sqrt{0.546^2 - 0.172 \cdot \log_{10}[A / (0.12 \cdot A_{0.01})]}}{0.086}$$

for temperate climate and :

$$Q(A) = \frac{-0.855 + \sqrt{0.855^2 - 0.556 \cdot \log_{10}[A / (0.07 \cdot A_{0.01})]}}{0.278}$$

for tropical / equatorial climate.

Then, the rain unavailability is predicted as the probability that the rain attenuation exceeds the Fade Margin FM :

$$P_{RAIN} = P(FM) = 10^{G(FM)}$$

The same result can be graphically derived from the [Time % vs. Rain Attenuation curve](#).

The hop Fade Margin is computed as a result of [Link Budget](#). In presence of heavy rainstorms, the thin water layer on the antenna radome (if used) produces an additional loss; the Fade Margin is reduced to take account of the "wet radome loss", a conservative figure being about 1 dB.

Quite often the rain unavailability prediction is transformed from a percentage probability to "minutes in one year". As a reference, the 0.01% probability is equivalent to about 50 min/year.

However, since the prediction method is based on long-term rain intensity statistics, also the estimated unavailability must be considered as an average, to be expected during a period of several years.

Advanced - Effect of cross-polarized interference

Signal depolarization caused by rain contributes to rain unavailability by reducing the discrimination to a cross-polar interfering signal. Typically, the problem arises in radio systems using a [co-channel frequency plan](#), with the same radio channel used on both polarizations.

The step-by-step procedure reported by ITU-R Rec. P.530 is as follows:

- Computation of the "reference attenuation" A_p :

$$A_p = 10^{[U - (C/I)_{\text{thr}}]/V}$$

where [U and V have been previously defined](#).

- Computation of the normalized parameter m (if $m > 40$, then $m = 40$):

$$m = 23.26 \cdot \text{Log}_{10} [A_p / (0.12 \cdot A_{0.01})]$$

where $A_{0.01}$ is the [attenuation exceeded for 0.01% of the time](#).

- Estimate of probability P_{XPR} (unavailability due to cross-polar interference):

$$P_{XPR} = 10^{[-8.35 + \sqrt{403 - m}]} \cdot 10^{-5}$$

Reliable estimates of P_{XPR} are in the range 10^{-2} to 10^{-5} .

Finally, the overall rain unavailability can be estimated as the larger of P_{XPR} (see above) and P_{RAIN} ([probability of unavailability due to rain attenuation only](#)).

This concludes Section 6 of the PPRLE. Please proceed to Herald Lab Exercise 6.

End of Section #6

SECTION 7 – FREQUENCY PLANNING AND INTERFERENCE

Summary

In this Session the use of different frequency bands for Point-to-Point radio systems is first considered and the ITU-R approach for RF channel arrangements is presented. Then, the various types of interference arising in P-P systems is examined, together with classification criteria. This allows to list the main interference sources and to give brief notes about each of them. Finally, the interference effects are discussed.

Use of frequencies in P-P links

"Radio Regulations" are the international agreements issued (and updated from time to time) by the International Telecommunications Union (ITU), as a result of WARC (World Administrative Radio Conference) meetings.

"Radio Regulations" specify which radio systems are allowed to use the various frequency bands, in the Radiofrequency Spectrum. In particular, point-to-point radio links are mentioned as "Fixed radio service" in frequency bands from VHF up to tens of GHz.

In the following, we briefly review the main criteria in the use of frequency bands in the range 1-60 GHz, for P-P applications.

Frequency Bands

The Table below reports the main applications of P-P radio links operating in different frequency ranges. The typical hop lengths and the most relevant propagation problems are indicated.

Frequency Band	Typical Hop Length	Propagation Problems	Typical Applications
< 5 GHz	50 - 60 km; long hops > 100 km	Multipath (rain not significant).	Long-haul networks; Over-the-sea hops; hops with reduced clearance.
5-11 GHz	40 - 50 km	Multipath, rain in some regions.	Long-haul networks.
12-15 GHz	20 - 40 km	Multipath and rain.	Short-haul networks; metropolitan links.
17-20 GHz	10 - 20 km	Rain.	Metropolitan links.
> 20 GHz	< 10 km	Rain, atmospheric absorption around 23 and 60 GHz.	Access networks; feeder links to BTS; P-MP; WLL (*).

(*) BTS = Base Transceiver Station in cellular networks; P-MP = Point-to-Multipoint systems; WLL = Wireless Local Loop.

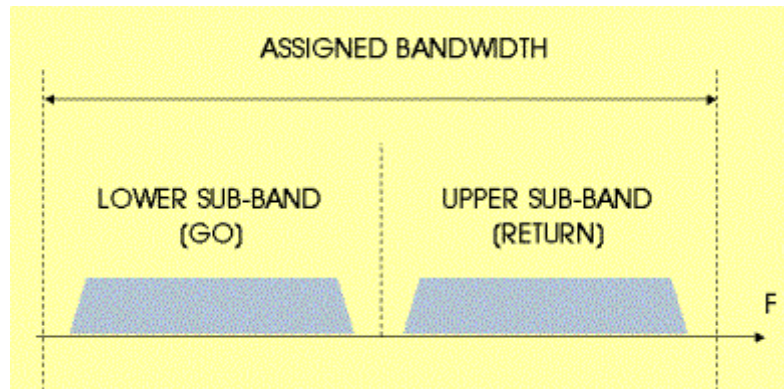
Note that, at frequencies above 15 GHz, the hop length limitation due to rain attenuation makes multipath outage almost negligible, even if multipath propagation should be a significant problem on longer hops.

Channel arrangements, ITU-R Recs.

We now consider frequency planning techniques, as implemented for P-P applications, in the context of different network models and with reference to frequency plans recommended by ITU-R..

Go - Return Frequency plans

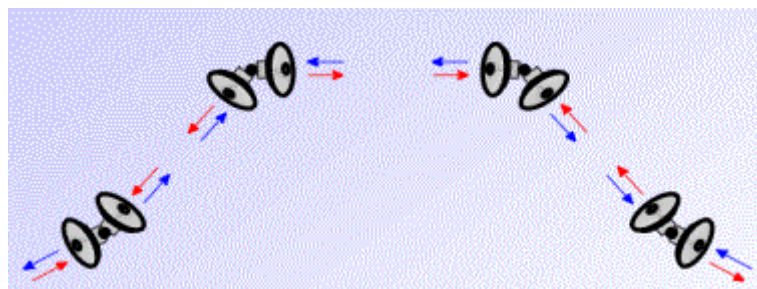
Typically, P-P radio links operate for bi-directional communications. To this end, the most common technique is to divide a frequency band, assigned to P-P radio systems, in two sub-bands (usually with the same bandwidth). One or more radio channels in one sub-band are used for transmission in one direction, while the corresponding radio channel(s) in the other sub-band transmit(s) in the opposite direction.



Sub-division of the assigned bandwidth in two sub-bands.

This explains why the two sub-bands are often labeled as "GO" and "RETURN" sub-bands, respectively.

In a long-haul network model the above technique is implemented as shown in the figure below.

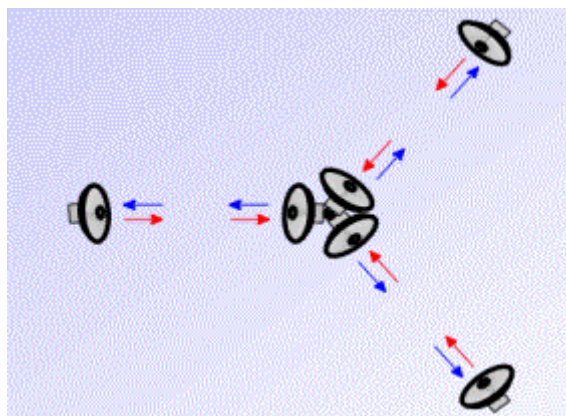


Use of sub-bands in a long-haul network (red arrows for lower sub-band, blue arrows for upper sub-band).

A given sub-band is used in a radio site for transmission in both directions. The other sub-band is used for reception only. Clearly, the condition is reversed at the two nearest sites.

So, the same frequency is never used in a radio site for both transmission and reception, in any direction. This avoids complex problems in decoupling receivers and transmitters located at the same site.

In a radio node (or star network model) the "Go / Return" technique is implemented as shown in the figure below.



Use of sub-bands in a star network.

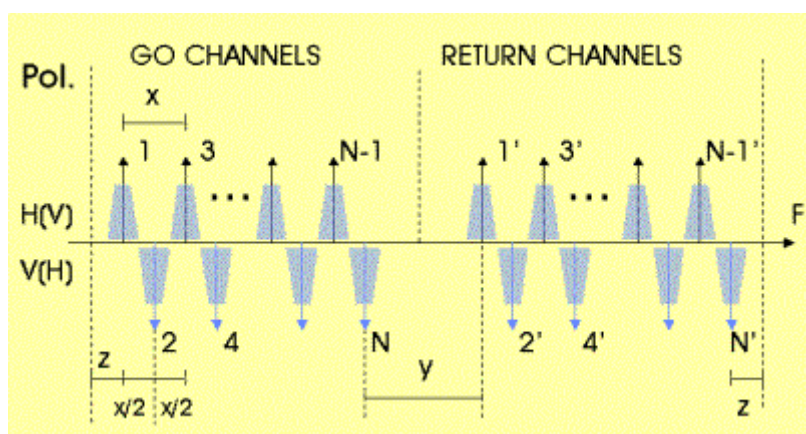
The radio node transmits in a given sub-band and receives in the other one. All the surrounding sites work in the opposite condition.

Interleaved and co-channel frequency arrangements

In a Go-Return frequency plan, each sub-band is divided in a number of radio channels. The way radio channels are positioned in each sub-band is called an "RF channel arrangement".

A number of ITU-R Recommendations deal with frequency arrangements in various frequency bands.

In an Interleaved Frequency Arrangement the adjacent RF channels are allocated on alternate polarizations, as shown in the figure below.

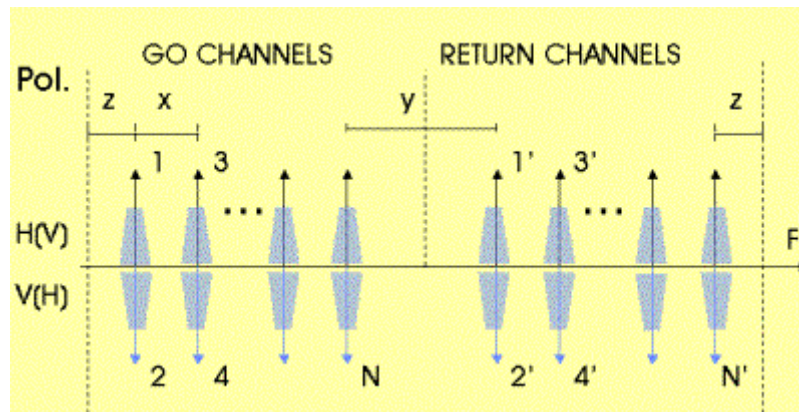


Interleaved frequency arrangement.

The frequency arrangement is defined by three parameters:

- X = channel spacing between co-polar channels (the channel spacing between cross-polar channels is $X/2$);
- Y = central guard band (key parameter to decouple Tx and Rx signals at a radio site);
- Z = edge guard band (to avoid interference from / to other radio systems in adjacent frequency bands).

On the other hand, in a Co-channel Frequency Arrangement, as shown in the figure below, the adjacent RF channels are allocated on both the orthogonal polarizations (H / V).



Co-channel frequency arrangement.

As in the case of the interleaved plan, three parameters (X , Y , Z) define the frequency arrangement. However, in the co-channel case, X is the channel spacing between co-polar and cross-polar channels.

Comment

Analog radio systems were mainly developed in frequency bands below 12 GHz, using the interleaved frequency arrangement, since analog signals are not suitable to accept a co-channel interference on the same radio hop.

Subsequently, the development of digital radio systems, mainly in frequency bands above 12 GHz, suggested the adoption of co-channel frequency plans, in order to get a higher efficiency in radio spectrum utilization (more radio channel packed in a given frequency band).

Presently, the co-channel frequency arrangement is recommended for use with digital systems (as an alternative to the interleaved plan) also in several frequency bands below 12 GHz.

Interference classification

The need arises of identifying various types of interfering signals and classifying them on the basis of different criteria. This allows the designer of a radio system to apply standard procedures to deal with each class of interfering signals.

Two aspects in the interference mechanisms can be considered : the source of the interfering signal and the impact of propagation conditions.

Source of Interference

A general classification of Interference sources is:

- Internal interference, when the interfering signal is emitted by a transmitter which is part of the same radio system of the interfered (victim) receiver.
- External interference, in the opposite case (the interfering signal is emitted by a transmitter which is part of a different radio system).

Usually, internal Interference in a radio network can be well estimated, since all the system parameters are under the control of the network designer.

On the other hand, external interference is more difficult to predict in detail, since not all the technical data about the interfering system (power levels, antenna pointing and diagrams, etc.) may be available at the designer of the interfered (victim) system. So, in most cases, external interference is taken into account with some approximation and including some conservative margin.

Coordination procedures are recommended in some cases by ITU-R to avoid interference between different radio systems, sharing a common frequency band.

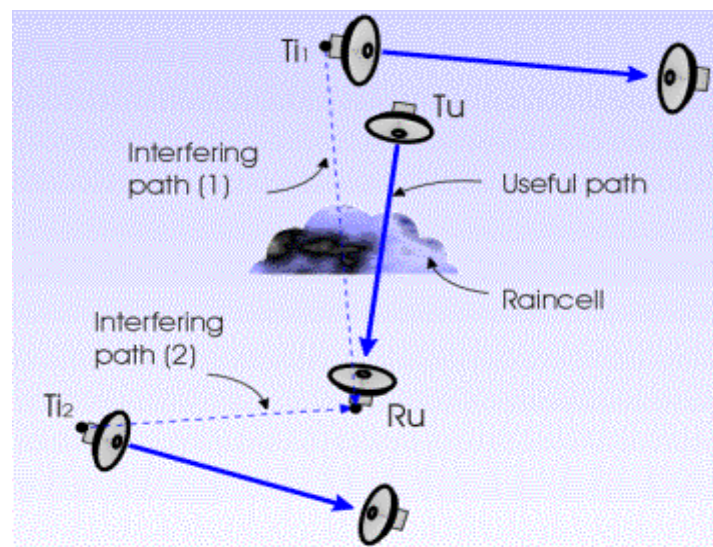
A more specific classification of interference sources refers to the transmitter / hop / radio system emitting the interfering signal:

- Co-site Interference (internal or external) : Produced by transmitters located at the same radio site where the interfered (victim) receiver is located.
- Same Hop Interference (internal only) : Produced by transmitters working on the same hop at the same frequency (co-channel, cross-pol. interference) or at adjacent frequencies (co-pol. or cross-pol. interference) with reference to the interfered (victim) receiver.
- Interference from other P-P Hops (internal or external): Produced by transmitters working on a different radio hop, at the same frequency (co-channel interference) or at adjacent frequencies with reference to the interfered (victim) receiver.
- Interference from other radio systems (external only): Produced by transmitters in radio systems other than P-P systems, sharing the same frequency band with P-P systems (e.g. satellite systems).

Propagation conditions

Another criterion to classify interference is related to the propagation conditions suffered by the interfering signal, compared with the propagation conditions which affect the useful (interfered) signal. We consider:

- Correlated Interference, when the interfering signal suffers the same propagation impairment as the useful signal. Specifically, in the case of rain events, this happens when the useful and the interfering paths are identical or so close that they are both affected by a raincell in the same way.
- Uncorrelated Interference, when the above conditions are not established, so that we can assume that additional attenuation (caused by multipath or rain) affects in a different measure the useful and the interfering signals. As a worst case assumption, we consider that the useful signal is received at the threshold level, while the interfering signal may be received with no additional attenuation (nominal power level).

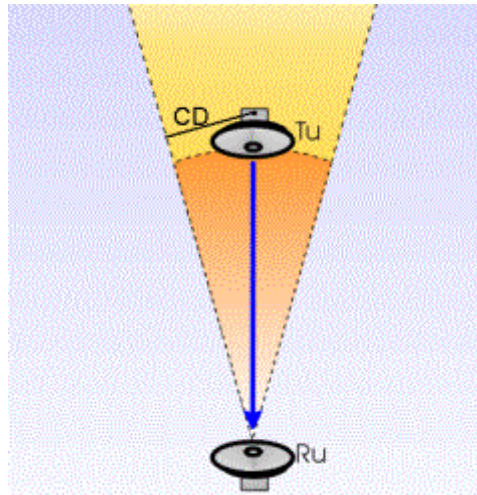


Correlated (1) and uncorrelated (2) interference paths when the useful path is affected by rain.

In some cases, the term "partially correlated" will be used, in particular when more precise models are available (like in the case of co-channel, cross-polarized same-hop interference, with rain or multipath fading).

The correlated / uncorrelated interference model appears as a rather approximated one (also the term "correlated" is not fully correct, as used in this context). However, even a rough model is useful to analyze the interference scenario in a simple way and worst case assumptions are often required to evaluate the most critical interference effects.

An example of a possible implementation of the rain correlation model is given in the figure below.



Interfering Tx in the yellow region produces a correlated interference;

in the blue and brown regions,

clauses a) and b) below are not satisfied, respectively;

(CD = Correlation Distance).

In this model, interference is assumed to be correlated if:

- 1) Separation from useful transmitter (Tu) to interfering path is below a given "Correlation Distance" C_D ;
- 2) Interfering path length is at least equal to the useful path length.

The above requirements guarantee that the interfering signal travels through the same raincell as the useful signal, along a path not shorter than the useful one.

Typical values of "Correlation Distance" are in the range 0.5-1.0 km (this is a fraction of the expected raincell size). However, a suitable choice of correlation distance allows to scale the model to local rain conditions. More specifically, zero correlation distance forces the model to assume as correlated only the interfering signals emitted at the same radio site as the useful signal; this may be an extremely conservative assumption.

Internal Interference sources

In this section we list a number of interference sources which may be present as internal interference in P-P radio networks.

For each interfering signal, information is given about frequency spacing and polarization, useful-to-interfering signal decoupling, and about the effect of propagation conditions (rain, multipath) on interference correlation or uncorrelation.

Co-site Interference

- Frequency spacing and polarization : central guard-band (minimum spacing); usually cross-pol. channels at the minimum spacing.
- Useful-to-Interfering signal decoupling : Tx & Rx signal filtering (NFD). Further decoupling depending on Tx/Rx implementation: if Tx & RX channels on the same antenna, then decoupling is produced by the branching system; if Tx & RX channels on the different antennas, then decoupling is given by the side-to-side antenna decoupling (see comments on antenna field performance vs. laboratory measurements).
- Effect of propagation: uncorrelated interference in any case (rain, multipath).

Same Hop - Co-channel, cross-polarized signal

- Useful-to-Interfering signal decoupling : only from antenna XPD (cross-polarization discrimination), zero frequency spacing, no filtering effect.
- Rain effects : even if the useful and the interfering signals travel along the same path, so that attenuation is correlated, the reduction in cross-polar discrimination due to rain makes the interference partially uncorrelated. The rain XPD model described in another session gives a practical tool to predict the overall effect.
- Multipath effects : partially uncorrelated Interference, due to XPD degradation under multipath propagation. The multipath prediction model gives a tool to estimate the overall effect of multipath attenuation and XPD degradation.

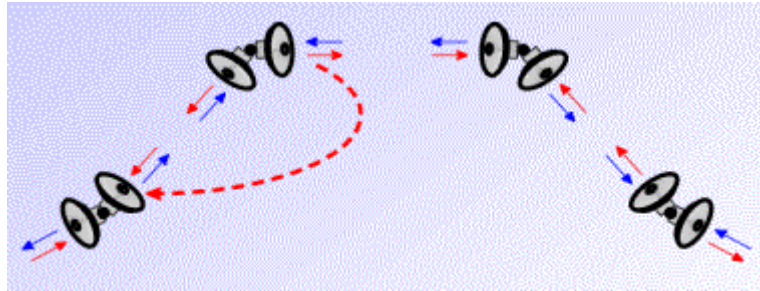
Same Hop - Adjacent channel, co-polarized signal

- Useful-to-Interfering signal decoupling : Tx & Rx signal filtering (NFD), depending on the RF channel spacing.
- Rain effects : correlated Interference;
- Multipath effects : partially uncorrelated interference (the ITU-R multipath models do not cover this type of interference).

Same Hop - Adjacent channel, cross-polarized signal

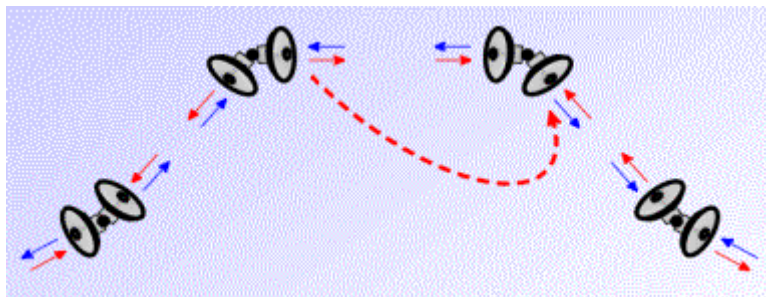
- Useful-to-Interfering signal decoupling : only from antenna XPD (cross-polarization discrimination), zero frequency spacing, no filtering effect.
- Rain effects : same as for co-channel, cross-polarized signal;
- Multipath effects : same as for co-channel, cross-polarized signal.

Long-haul Networks - Backward Interference



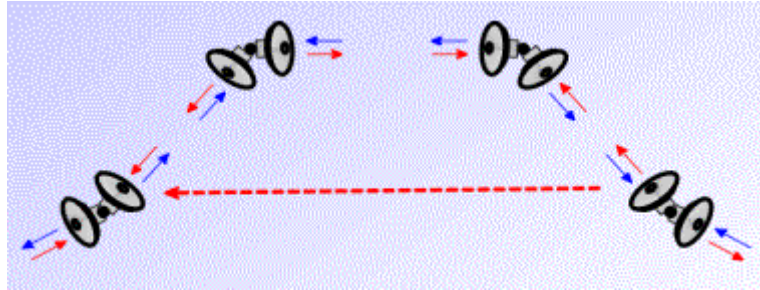
- Frequency spacing and polarization : (usually) co-channel, cross-polar.
- Useful-to-Interfering signal decoupling : from Tx antenna front-to-back decoupling (see comments on antenna field performance vs. laboratory measurements).
- Rain effects : correlated interference (same path for useful and interfering signals).
- Multipath effects : uncorrelated Interference (useful and interfering transmitters are co-located, but signals are emitted by different antennas; equivalent to a Tx diversity system).

Long-haul Networks - Forward Interference



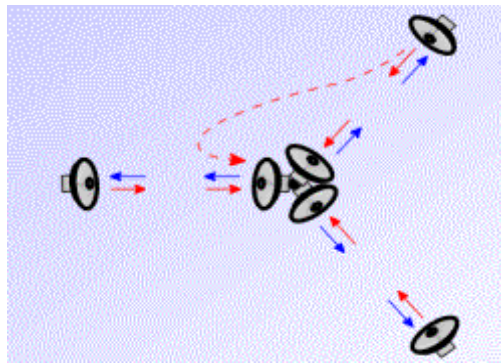
- Frequency spacing and polarization : (usually) co-channel, cross-polar.
- Useful-to-Interfering signal decoupling : from Rx antenna front-to-back decoupling (see comments on antenna field performance vs. laboratory measurements).
- Rain effects : uncorrelated interference (different paths for useful and interfering signals).
- Multipath effects : uncorrelated Interference

Long-haul Networks - Over-reach Interference



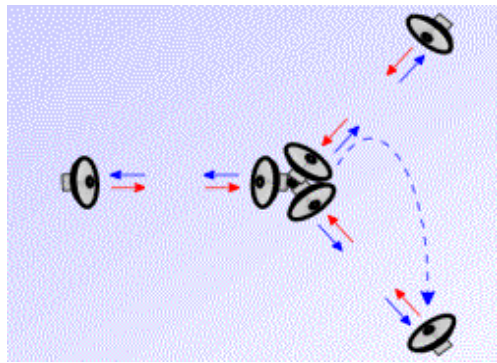
- Frequency spacing and polarization : co-channel, co-polar.
- Useful-to-Interfering signal decoupling : Tx and Rx Antenna angular discrimination (if hops are not aligned). Additional Free Space Loss (interfering path length)
- Rain effects : correlated interference in the critical case of almost aligned hops.
- Multipath effects : uncorrelated interference.

Star Networks - Up-link Interference



- Frequency spacing and polarization : co-channel, co-polar (worst case).
- Useful-to-Interfering signal decoupling : Rx (node) antenna angular discrimination. Tx & Rx signal filtering (NFD) if not co-channel.
- Rain effects : uncorrelated Interference.
- Multipath effects : uncorrelated Interference.

Star Networks - Down-link Interference



- Frequency spacing and polarization : co-channel, co-polar (worst case).
- Useful-to-Interfering signal decoupling : Tx (node) antenna angular discrimination. Tx & Rx signal filtering (NFD) if not co-channel.
- Rain effects : correlated interference.
- Multipath effects : uncorrelated interference.

Degradation due to Interference

Performance degradation caused by interference can be evaluated following a two-step process:

- To estimate the power level of the interfering signal at the (useful) receiver input. The interfering power is evaluated under two alternative assumptions: (1) useful signal received at nominal power level; (2) useful signal received at threshold level.
- To estimate the effect of a given interference power on the interfered receiver. This depends on a number of system parameters, including the receiver threshold, the modulation format and interference sensitivity.

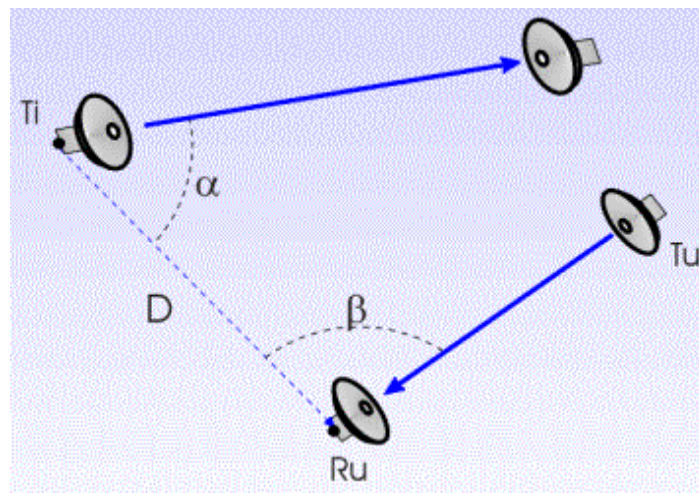
Let us consider four interference classes:

- Same hop interference: Degradation caused by co-channel or adjacent-channel interference in the same radio hop is usually included in outage prediction models. This has been discussed in previous sessions, in connection with [multipath propagation](#) and [rain attenuation](#).

- Co-site interference (internal interference): this is usually considered as part of the radio system design; equipment manufacturer gives specifications about the required decoupling between Tx and Rx radio channels, for the suggested system configurations (Tx and Rx channels on the same antenna or on separate antennas).
- Co-site interference (external interference): in this case, coexistence is required of different radio systems and a general analysis is not possible. High level interfering signals (even at a quite different frequency) may be responsible of anomalous receiver response, related to Rx saturation and non-linearity, intermodulation, spurious emissions, etc. This point will not be considered in the following.
- Interference coming from other radio hops: this case is discussed below.

Interference power estimate

The figure defines the geometrical parameters in the interference scenario.



Interference from site Ti to useful receiver Ru: definition of geometrical parameters.

As a first approach, the Basic Radio Link equation (used to predict Rx power in the useful hop) gives an estimate of interference power I_R at the useful receiver input:

$$I_R = P_T + G_T(\alpha) + G_R(\beta) - FSL \quad (dBm)$$

where: P_{IR} = output power (dBm) at the interfering Tx;

$G_T(\alpha)$ = Tx antenna gain (dB) in the direction of the interfered (victim) receiver;

$G_R(\beta)$ = Rx antenna gain (dB) in the direction of the interfering transmitter;

FSL = Free Space Loss (dB) over the T_i to R_u path.

The Net Filer Discrimination (NFD) gives the measure of the interfering signal attenuation, as a result of the useful receiver selectivity. If the interfering signal spectrum is within the Rx filter passband, then $NFD=0$ dB.

The signal-to-interference ratio, under the assumption of no additional attenuation of the useful signal, is defined as "Unfaded S/I" $(S/I)_U$ and is computed as:

$$(S/I)_U = P_R - I_R + NFD \quad (dB)$$

where P_R is the nominal useful power at the receiver input and I_R is given above.

Similarly, the signal-to-interference ratio, under the assumption that the useful signal is at the threshold level, is defined as "Faded S/I" $(S/I)_F$. For uncorrelated interference (no attenuation suffered by the interfering signal) it is computed as:

$$(S/I)_F = P_{TH} - I_R + NFD = (S/I)_U - FM \quad (dB)$$

where: P_{TH} = useful receiver threshold;

$FM = P_R - P_{TH}$ = Fade Margin in the useful hop.

On the other hand, for correlated interference (same attenuation on the useful and interfering signals), we have:

$$(S/I)_F = (S/I)_U$$

Up to now, we have assumed that no obstruction exists between the interfering Tx and the useful (victim) Rx. If the interfering path is not perfectly clear, a clearance analysis should be performed.

A more general approach to path loss prediction for interfering signals is given by ITU-R Rec. P.452 ("Prediction procedure for the evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz").

In that recommendation, all the propagation mechanisms which can contribute to interference power reception at the useful (victim) receiver, are considered:

- line-of-sight;
- diffraction;
- tropospheric scatter;
- surface and elevated ducting;
- hydrometeor scatter.

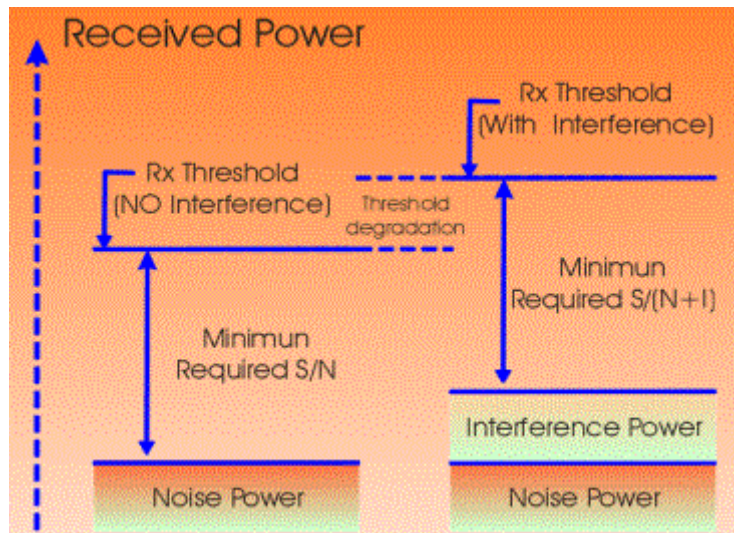
This allows a quite detailed analysis of interference levels, which cannot be summarized in these notes.

Effect of Interference

The interference effect can be estimated by assuming that the interference power is equivalent to an additional noise power at the receiver.

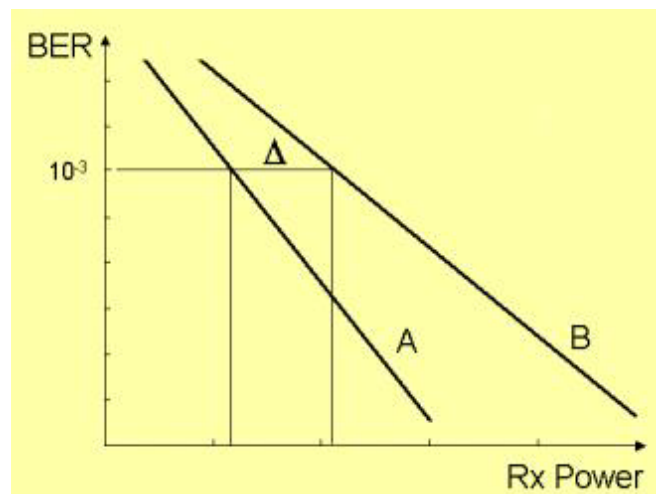
This assumption allows to predict the receiver performance with satisfactory approximation, in particular for adjacent-channel interference and when we have multiple interference. In most cases it is only slightly pessimistic. Alternatively, for co-channel interference, it may be advisable to refer to the measured Rx performance.

The chart below gives a graphical interpretation of threshold degradation caused by the combined impairment of noise and interference.



Increase of Rx threshold power due to the combined disturbance of noise and interference power.

The overall result of an interfering signal on system performance is to shift the BER vs. Rx power curve to the right, as in the figure below.



BER vs. Rx power without (A) and with (B) the presence of interference; Δ = Rx threshold degradation.

The two curves allow to estimate the performance degradation for any BER value. Note that the figure above refers to an interfering signal, with given C/I ratio, modulation format and frequency spacing.

This concludes Section 7 of the PPRLE. Please proceed to Herald Lab Exercise 7.

End of Section #7

SECTION 8 – ITU OBJECTIVES

Summary

In this Session ITU performance objectives are discussed. Under some aspects the matter is rather complex, so a brief history and overview of ITU recommendations is first presented. Then, more details are given about ITU-T and ITU-R error performance and availability objectives and the most significant points of relevant recommendations are outlined. Finally, the impact of propagation impairments on objective compliance is discussed.

Overview

In recent years, International Telecommunication Union (ITU) committees produced several Recommendations to set Performance Objectives for Telecommunication Systems. It is not always easy to understand how different recommendations are linked together and which is the correct one to refer in particular cases.

In the following sections, we try to give a brief review of ITU performance objectives and some simple indication on the use of ITU Recs, even if it will not be possible to go in details about many related questions.

ITU-T and ITU-R Recommendations

Dealing with ITU performance objectives, it is useful to clarify the role of ITU-T and ITU-R, in the framework of ITU activities.

ITU-T is mainly involved in regulating the end-to-end service and performance of telecommunication networks and systems. On the other hand, ITU-R is devoted to radio systems only (not limited to communications systems, but including radioastronomy, earth monitoring, etc.).

As a consequence, the ITU-T recommendations on performance objectives are "media independent", that is they are addressed to the end-to-end performance of a telecommunication link, independently of the transmission system(s) used (cable, fiber, or radio).

ITU-R recommendations on performance objectives refer to radio communications only. They derive from (and must be in agreement with) ITU-T recommendations, since a link regulated by ITU-T may be implemented (partially or totally) using radio-relay systems.

Unavailability and Error Performance Objectives

ITU objectives are organized as:

- Unavailability objectives: they refer to conditions required to get an operating link; in general terms, we can state that unavailability is caused by equipment failures or by other events that produce an enduring loss of signal or an unacceptable signal degradation.
- Error Performance (quality) objectives: they refer to the received signal quality and are evaluated during the available time only. So the definition of unavailability is fundamental both for error performance and for unavailability evaluation.

Testing the compliance of a given telecommunication link with ITU objectives, we need:

- first to identify unavailability periods and check the Unavailability Objectives;
- then to check the Error Performance Objectives during available time.

A brief history and overview of ITU Recs

The recent history of ITU performance Recs starts with the approval of ITU-T Rec. G.821, at the end of 70's.

At that time, telecommunication systems were mainly addressed to the telephone (voice) service and digital transmission was almost exclusively based on the 64 kbit/s PCM channel. Data services were expected to grow through ISDN networks, again based on the 64 kbit/s channel.

For that reason, also performance objectives in G.821 make reference to the 64 kbit/s channel (or multiples, but anyway below the primary rate), without considering the actual bit rate of transmitted signals.

Error Performance and Availability objectives, derived by ITU-R from G.821, apply to bit rates below the primary rate. Suitable rules have been used to translate error performance measurements obtained at the system bit rate to the 64 kbit/s level.

Such problems were not solved until ITU-T Rec. G.826 was approved (1990). The new recommendation introduces two significant modifications, with respect to G.821:

- objectives apply at the system bit rate, not on the 64 kbit/s channel;
- performance parameters are no longer based on bit error rate (BER), but on errored blocks.

The whole set of ITU-R Recs. had to be revised. As a first step, two recommendations were approved (F.1092 and F.1189), which apply to the national and international portion of the Hypothetical Reference Path (HRP).

The practical use of these recommendations was not straightforward, since the HRP concept does not match closely with network configurations found in the real world.

At the same time, in the ITU-T environment, it was recognized the need for performance objectives specifically issued for SDH networks. ITU-T Rec. G.828 was approved in the year 2000 and defines error performance objectives for SDH path.

To clarify the applicability of G.826 and G.828 to SDH systems, we quote from G.828: "*... this Recommendation is the only Recommendation required for designing the error performance of synchronous digital paths. (...) It is not required to apply this Recommendation to SDH paths using equipment designed prior to the adoption of Recommendation G.828 in March 2000. Performance objectives for paths using equipment designed prior to this date are given in Recommendation G.826.*"

ITU-R Recs. F.1397 and F.1491 take account of both G.826 and G.828 and apply, respectively, to international and national real radio links.

The Table below gives a summary of the evolution of significant ITU-T and ITU-R recommendations.

ITU-T Rec.	ITU-R Rec.	Applicable to
G.821 (1978)	F.594	<u>HRDP</u> (64 kbit/s ch.)
G.821 (1978)	F.634, F.696, F.697	Real links (64 kbit/s ch.)
G.826 (1990)	F.1092, F.1189	<u>HRP</u> (PDH, SDH)
G.826 / G.828 (2000)	F.1397, F.1491	Real links (PDH, SDH)

Evolution of ITU-T and ITU-R error performance Recs.

Definitions

Primary rate: the first level of PCM multiplexing (that is E1 rate = 2.048 Mbit/s in Europe and other countries; T1 rate = 1.544 Mbit/s in the USA and other countries).

System bit rate: the gross bit rate of the transmitted signal, after multiplexing operation and including any service and controlling bits.

Block Allowance: a component of the overall threshold objective, which is allocated independently of the connection length.

Block (of bits): a set of consecutive bits associated with the signal path.

Hypothetical Reference Connection (HRX): used in the context of ITU-T G.821, a 27,500 km link including an international portion (High Grade objectives) and National portions (High, Medium, and Local Grade objectives).

Hypothetical Reference Path (HRP): used in the context of ITU-T G.826, a 27,500 km international link including the two terminal countries and up to four intermediate countries.

Hypothetical Reference Digital Path (HRDP): used in the context of ITU-R F.594, a 2,500 km radio link, subdivided in radio sections of at least 280 km.

Advanced - ITU-T Error Performance Recs.

G.821 - ITU-T Rec. G.821 defines error performance parameters and objectives of a Hypothetical Reference Connection (HRX), at a bit rate below the primary rate.

The error performance objectives are stated for each direction of a N x 64 kbit/s connection ($1 \leq N \leq 32$ or 24 chs.), independently of the transmission medium.

The following error performance events and parameters are defined:

- **Errored Second (ES)** : a one-second period in which one or more bits are in error.
- **Severely Errored Second (SES)** : a one-second period which has a $BER \geq 10^{-3}$.
- **Errored Second Ratio (ESR)** : the ratio of ES to total seconds in available time during a fixed measurement interval.
- **Severely Errored Second Ratio (SESR)** : the ratio of SES to total seconds in available time during a fixed measurement interval.

The end-to-end error performance objectives for the 27500 km Hypothetical Reference Connection (HRX) are given in the Table below, referring to the three classes (high-, medium- and local-grade).

	ESR	SESR
End-to-End	< 0.08	< 0.002

High grade	0.032	0.0004 (1)
Medium grade	0.012	0.00015 (1)
Local grade	0.012	0.00015

(1) For radio-relay systems a block allowance of 0.0005 *SESR* can be added to a 2 500 km HRDP

G.821 error performance objectives.

G.826 - ITU-T Rec. G.826 defines error performance parameters and objectives of a Hypothetical Reference Path (HRP), for international Constant Bit Rate (CBR) digital paths at or above the primary rate.

The recommendation is applicable to each direction of the 27500 km HRP. It applies as well for PDH, SDH and cell-based networks. It is independent of the transmission medium.

The important difference between ITU-T Rec. G.821 and ITU-T Rec. G.826 is that in G.826 the parameters are based on errored blocks and not on errored bits.

The parameters defined in ITU-T Rec. G.826 are based on the following events:

- **Errored Block (EB)** : a block in which one or more bits are in error.
- **Errored Second (ES)** : a one-second period with one or more errored blocks.
- **Severely Errored Second (SES)** : a one-second period which contains more than 30% errored blocks or at least one defect in the received signal.
- **Background Block Error (BBE)**: an errored block not occurring as part of an SES.

The following error performance parameters are defined:

- **Errored Second Ratio (ESR)**: the ratio of ES to total seconds in available time during a fixed measurement interval.
- **Severely Errored Second Ratio (SESR)**: the ratio of SES to total seconds in available time during a fixed measurement interval.
- **Background Block Error Ratio (BBER)**): the ratio of BBE to total blocks in available time during a fixed measurement interval. The count of total blocks excludes all blocks during SESs.

The end-to-end error performance objectives for a 27 500 km HRP are specified in the Table below. The path fails to meet the error performance requirements if any of the objectives is not met.

Mbit/s	Bits / Block	ESR	SESR	BBER
1.5 - 5	800 - 5000	0.04	0.002	2×10^{-4}

> 5 - 15	2000 - 8000	0.05	0.002	2×10^{-4}
> 15 - 55	4000 - 20000	0.075	0.002	2×10^{-4}
> 55 - 160	6000 - 20000	0.16	0.002	2×10^{-4}
> 160	15000 - 30000	t.b.d.	0.002	1×10^{-4}

G.826 end-to-end error performance objectives.

The suggested measurement interval is one month. For radio-relay systems the objectives should be respected for any month.

The end-to-end objectives are divided into one national portion and one international portion. The allocation rules are rather complex and are based on a block allocation and a distance allocation (multiples of 500 km). Each National Portion is allocated at least a 17.5% of the end-to-end objectives.

G.828 - ITU-T Rec. G.828 defines error performance parameters and objectives for SDH systems only (application of G.826 and G.828 was discussed above). G.828 uses the error performance events and parameters as defined by Rec. G.826. Two additional definitions are:

- **Severely Errored Period (SEP):** a sequence of between 3 to 9 consecutive SES; the sequence is terminated by a second which is not a SES
- **Severely Errored Period Intensity (SEPI):** the number of SEP events in available time divided by the total available time in seconds

The end-to-end objectives defined by ITU-T Rec. G.828 for a 27 500 km HRP in terms of the error parameters (ESR, SESR, BBER) are shown in the Table below (SEPI objectives are not indicated, since further study is required).

Bit rate (Mbit/s)	Bits / Block	ESR	SESR	BBER
1,664	2000	0.01	0.002	5×10^{-5}
2,240	2000	0.01	0.002	5×10^{-5}
6,848	2000	0.01	0.002	5×10^{-5}
48,960	8000	0.02	0.002	5×10^{-5}
150,336	8000	0.04.	0.002	1×10^{-4}
601,344	8000	Not spec.	0.002	1×10^{-4}

G.828 end-to-end error performance objectives.

The objectives applicable to a real path are derived using allocation principles for international and national portions. Again, this is based on block allocation and on distance allocation (multiples of 100 km).

Advanced - Error performance in a radio link

ITU-R Recs on error performance, derived by ITU-T Recs introduced in the previous section, are now discussed.

Error objectives for real links below the primary rate

The error performance objectives for real links below the **primary rate** are based on **ITU-T Rec. G.821**, using the same definitions of Errored Second Ratio (ESR) and of Severely Errored Second Ratio (SESR). They are specified in three ITU-R recommendations, referring to high-, medium- and local-grade, respectively.

A summary is given in the Table below.

	ESR	SESR
End-to-End	< 0.08	< 0.002
High grade (1)	0.0032 x	0.00054 x
ITU-R Rec. F.634	L / 2500	L / 2500
Medium grade	0.012	0.0004
ITU-R Rec. F.696		
Local grade	0.012	0.00015
ITU-R Rec. F.697		

(1) Length L (km) in the range 280 to 2500 km. For L < 280 km, a linear scaling can be used.

Error performance objectives for real digital radio-relay systems, below the primary rate.

Error objectives in the international portion of a real link at or above the primary rate

ITU-R Rec. F.1397 gives the performance objectives for the international portion of a real link. A distinction has to be made between terminating countries and transit (or intermediate) countries.

Moreover, we distinguish PDH and SDH systems, referring to ITU-T Recs. [G.826](#) and [G.828](#), respectively.

Error Performance Objectives (EPO) are expressed by a general formula:

$$EPO = B \times (L_{\text{link}} / L_R) + C$$

where:

EPO can be replaced by SESR, ESR, or BBER, as appropriate;

B, C are numerical values, given in Rec. F.1397 tables;

L_{link} is the link length;

L_R is the reference length (2500 km).

The SEPI parameter, which is defined by ITU-T G.828, is ignored. The reason is that no propagation model to predict SEPI is presently available and the need for SEPI objectives is still under study.

Application of the general formula given above leads to the results shown in the tables below. In that formula, B and C are functions of parameter B_R (= block allowance ratio), to be selected by the network operator, in the range 0 to 1. That's why all the objectives are not expressed as a single value, but as a range, corresponding to $B_R=0$ and $B_R=1$.

Two link lengths (L_1 , L_2) are considered in the tables; for any other length (in the 50 to 2500 km range), the following rules must be applied:

- up to L_1 , the objective is proportional to the link length;
- for a length between L_1 and L_2 , the objective is computed by linear interpolation.

Bit rate (Mbit/s)	Length [km]	ES [s / month]	SES [s / month]	BBER ($\times 10^{-6}$)
1,664	1000	520 - 1040	104 - 208	1.0 - 2.0
	2500	1300 - 1820	260 - 364	2.5 - 3.5
2,240	1000	520 - 1040	104 - 208	1.0 - 2.0
	2500	1300 - 1820	260 - 364	2.5 - 3.5
6,848	1000	520 - 1040	104 - 208	1.0 - 2.0
	2500	1300 - 1820	260 - 364	2.5 - 3.5
48,960	1000	1040 - 2080	104 - 208	1.0 - 2.0
	2500	2600 - 3640	260 - 364	2.5 - 3.5

150,336	1000	2080 - 4160	104 - 208	2.0 - 4.0
	2500	5200 - 7280	260 - 364	5.0 - 7.0

F.1397 error performance objectives for SDH international links, intermediate countries.

Bit rate (Mbit/s)	Length [km]	ES [s / month]	SES [s / month]	BBER ($\times 10^{-6}$)
1.5 - 5	1000	2080 - 4160	104 - 208	4.0 - 8.0
	2500	5200 - 7280	260 - 364	10.0 - 14.0
> 5 - 15	1000	2600 - 5200	104 - 208	4.0 - 8.0
	2500	6500 - 9100	260 - 364	10.0 - 14.0
> 15 - 55	1000	3900 - 7800	104 - 208	4.0 - 8.0
	2500	9750 - 13650	260 - 364	10.0 - 14.0
>55 - 160	1000	8320 - 16640	104 - 208	4.0 - 8.0
	2500	20800-29120	260 - 364	10.0 - 14.0

F. 1397 error performance objectives for PDH international links, intermediate countries.

Bit rate (Mbit/s)	Length [km]	ES [s / month]	SES [s / month]	BBER ($\times 10^{-6}$)
1,664	500	260 - 520	52 - 104	0.5 - 1.0
	2500	1300 - 1560	260 - 312	2.5 - 3.0
2,240	500	260 - 520	52 - 104	0.5 - 1.0

	2500	1300 - 1560	260 - 312	2.5 - 3.0
6,848	500	260 - 520	52 - 104	0.5 - 1.0
	2500	1300 - 1560	260 - 312	2.5 - 3.0
48,960	500	520 - 1040	52 - 104	0.5 - 1.0
	2500	2600 - 3120	260 - 312	2.5 - 3.0
150,336	500	1040 - 2080	52 - 104	1.0 - 2.0
	2500	5200 - 6240	260 - 312	5.0 - 6.0

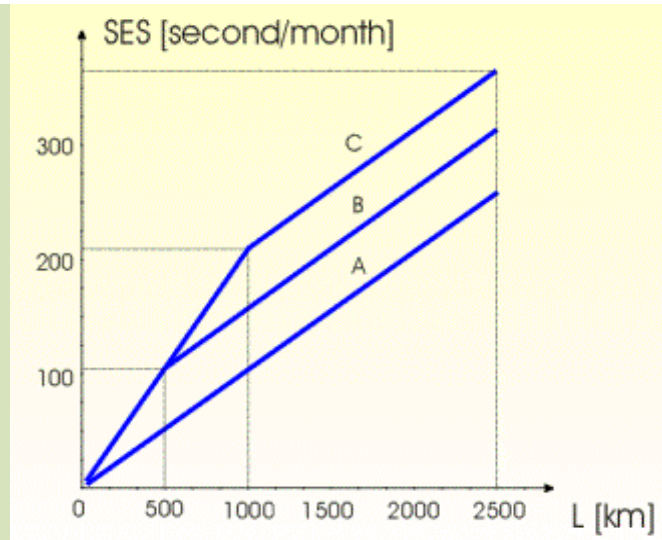
F.1397 error performance objectives for SDH international links,terminating countries.

Bit rate (Mbit/s)	Length [km]	ES [s / month]	SES [s / month]	BBER (x 10 ⁻⁶)
1.5 - 5	500	2080 - 4160	52 - 104	2.0 - 4.0
	2500	5200 - 6240	260 - 312	10.0 - 12.0
> 5 - 15	500	2600 - 5200	52 - 104	2.0 - 4.0
	2500	6500 - 7800	260 - 312	10.0 - 12.0
> 15 - 55	500	3900 - 7800	52 - 104	2.0 - 4.0
	2500	9750 - 11700	260 - 312	10.0 - 12.0
>55 - 160	500	8320 - 16640	52 - 104	2.0 - 4.0
	2500	20800-24960	260 - 312	10.0 - 12.0

F. 1397 error performance objectives for PDH international links,terminating countries.

Note that, while ESR and BBER objectives are dependent on the bit rate, the SESR objective is applicable to any rate (from 1.5 to 160 Mbit/s) and it is common to SDH and PDH systems.

The figure below gives an example referring to the significant case of SESR objective for SDH or PDH links.



SES objective for SDH and PDH international links (Rec. F.1397). A) Block Allowance $B_R = 0$, Intermediate and terminating countries. B) $B_R = 1$, terminating countries. C) $B_R = 1$, intermediate countries.

Error objectives in the national portion of a real link at or above the primary rate

ITU-R Rec. F.1491 gives the performance objectives for the national portion of a real link, which is divided in 3 sections:

- the long-haul section (from the International Gateway to the Primary, Secondary, or Tertiary Center);
- the short-haul section (from the Primary, Secondary, or Tertiary Center to the Local Exchange);
- the access section (from the Local Exchange to the path end-point).

For long-haul sections, the objectives are listed in the Tables below. A parameter A1 (= block allowance for long-haul sections) is left to be selected by the network operator, in the range 1% to 2% (Rec. F.1491 indicates that 1% should be a typical value). That's why all the objectives are not expressed as a single value, but as a range, corresponding to $A1=0.01$ and $A1=0.02$.

Two link lengths ($L1$, $L2$) are considered in the tables; for any other length (in the 50 to 2500 km range), the following rules must be applied:

- up to $L1$, the objective is proportional to the link length;
- for a length above $L1$, the objective is computed by linear interpolation or extrapolation of the values given for $L1$ and $L2$.

Bit rate	Length	ES	SES	BBER
(Mbit/s)	[km]	[s / month]	[s / month]	($\times 10^{-6}$)

1,664	100	312 - 572	62 - 114	0.6 - 1.1
	1000	780 - 1040	156 - 208	1.5 - 2.0
2,240	100	312 - 572	62 - 114	0.6 - 1.1
	1000	780 - 1040	156 - 208	1.5 - 2.0
6,848	100	312 - 572	62 - 114	0.6 - 1.1
	1000	780 - 1040	156 - 208	1.5 - 2.0
48,960	100	624 - 1044	62 - 114	0.6 - 1.1
	1000	1560 - 2080	156 - 208	1.5 - 2.0
150,336	100	1248 - 2088	62 - 114	1.2 - 2.2
	1000	3120 - 4160	156 - 208	3.0 - 4.0

F.1491 error performance objectives for SDH links in the long-haul network.

Bit rate (Mbit/s)	Length [km]	ES [s / month]	SES [s / month]	BBER ($\times 10^{-6}$)
1.5 - 5	100	1248 - 2088	62 - 114	2.4 - 4.4
	1000	3120 - 4160	156 - 208	6.0 - 8.0
> 5 - 15	100	1560 - 2610	62 - 114	2.4 - 4.4
	1000	3900 - 5200	156 - 208	6.0 - 8.0
> 15 - 55	100	2340 - 3915	62 - 114	2.4 - 4.4
	1000	5850 - 7800	156 - 208	6.0 - 8.0
> 55 - 160	100	4992 - 8352	62 - 114	2.4 - 4.4
	1000	12480 - 16640	156 - 208	6.0 - 8.0

F.1491 error performance objectives for PDH links in the long-haul network.

The error objectives for long-haul sections are the same defined for the international portion.

For short-haul and access sections, the objectives are listed in the Tables below. Block allowances for short-haul sections and for access sections are parameters left to the network operator, in the range 7.5% to 8.5%. That's why all the objectives are not expressed as a single value, but as a range, corresponding to block allowance 0.075 and 0.085.

Bit rate (Mbit/s)	ES [s / month]	SES [s / month]	BBER ($\times 10^{-6}$)
1,664	1950 - 2210	390 - 442	3.75 - 4.25
2,240	1950 - 2210	390 - 442	3.75 - 4.25
6,848	1950 - 2210	390 - 442	3.75 - 4.25
48,960	3900 - 4420	390 - 442	3.75 - 4.25
150,336	7800 - 8840	390 - 442	7.50 - 8.50

F.1491 error performance objectives for SDH links in the short-haul or access network.

Bit rate (Mbit/s)	ES [s / month]	SES [s / month]	BBER ($\times 10^{-6}$)
1.5 - 5	7800 - 8840	390 - 442	15.0 - 17.0
> 5 - 15	9750 - 11050	390 - 442	15.0 - 17.0
> 15 - 55	14625 - 16575	390 - 442	15.0 - 17.0
> 55 - 160	31200 - 35360	390 - 442	15.0 - 17.0

F.1491 error performance objectives for PDH links in the short-haul or access network.

Again, we note that, while ESR and BBER objectives are dependent on the bit rate, the SESR objective is applicable to any rate (from 1.5 to 160 Mbit/s) and it is common to SDH and PDH systems.

Practical rules in applying ITU-R Recs

Two problems may arise in applying ITU-R Recs F.1397 and F.1491:

- selecting to use SDH or PDH objectives;
- apportioning section objectives on a single hop or on a distance basis.

How to identify SDH and PDH sections - Practical rules are:

- a radio link composed by two terminals with optical and electrical STM-N interface is a SDH section, so SDH objectives shall be used.
- a radio link composed by two terminals with optical or electrical PDH interface at both terminal is a PDH section, independently from the rate carried over the radio channel, so the PDH objectives shall be used.
- a radio link composed by one terminal with optical or electrical PDH interface and one terminal with STM-n interface is a SDH section, so the SDH objectives shall be used.

How to apportion Section objectives to each hop - Performance objectives given by ITU-R Recs apply to the overall link, even in the case of multi-hop links. Allocation of the objectives to each hop is under the responsibility of the network operator.

The network operator can allocate objectives in a way proportional to the hop lengths, or different criteria can be followed, to overcome particular problems. This gives the network operator some flexibility in link design.

Note that multipath propagation models indicate that predicted outage is not proportional to the hop length, but approximately to the third power of the hop length.

As an example, let us suppose that a three-hop link has to be designed, with one over-the-sea hop. The designer is free to decide to allocate most of the overall objective to the hop over the sea (in order to reduce cost and to overcome propagation problems), while the objectives assigned to the other two hops are less then proportional to the hop lengths.

How to apportion Short-haul or Access section objectives on a distance

basis - Objectives for short-haul and access sections are given by ITU-R Rec. F.1491 on a block allowance basis (independent on section length).

Objective apportioning on a distance basis is left to the network operator. This is mainly based on the fact that the apportioning process is strongly dependent on:

- network architecture, network protection policy, maintenance policy, etc.;
- access network structure (from high density urban environment to rural environments);
- guaranteed Quality of Service.

All the above factors are defined or managed by the network operator.

The suggested procedure is to identify a "typical" length of short-haul or access sections and then to use the typical length to scale down the objectives for sections of any length.

Advanced - Unavailability Objectives

Unavailability is defined by ITU-T Rec. G.826. An unavailability period begins when ten consecutive SES events are observed (the ten seconds are part of the unavailability period). When ten consecutive non-SES events are observed, the unavailability period closes (the ten seconds are part of the new availability period).

The SES definition is the same given in the context of Error Performance Recs.

ITU-T Recs. G.826 and G.827

The following availability parameters are defined by ITU-T Rec. G.826:

- **Availability ratio (AR)** : ratio of total available time to the duration of the observation period;
- **Mean time between outages (Mo)** : average duration of any continuous interval during which the link is available.

The Unavailability Ratio (UR) is the complementary parameter to AR, so that $AR + UR = 1$.

From the Mo parameter, the "Outage Intensity" (OI) is derived as:

$$OI = 8760 / Mo$$

OI expresses the average number of unavailability periods in one year. Mo and OI have been recently introduced; this new parameters are needed since the Quality of Service may be affected not only by the total unavailable time, but also by the number of unavailability periods.

Availability objectives for International and National digital systems are given by ITU-T Rec. G.827, as media independent objectives. Two types of objectives are specified:

- mean values, that is the ensemble average of all paths of a given category in a country;
- worst-case values, that is the minimum acceptable value for individual paths.

The objectives apply to observation periods of one year. They are intended for the following purposes:

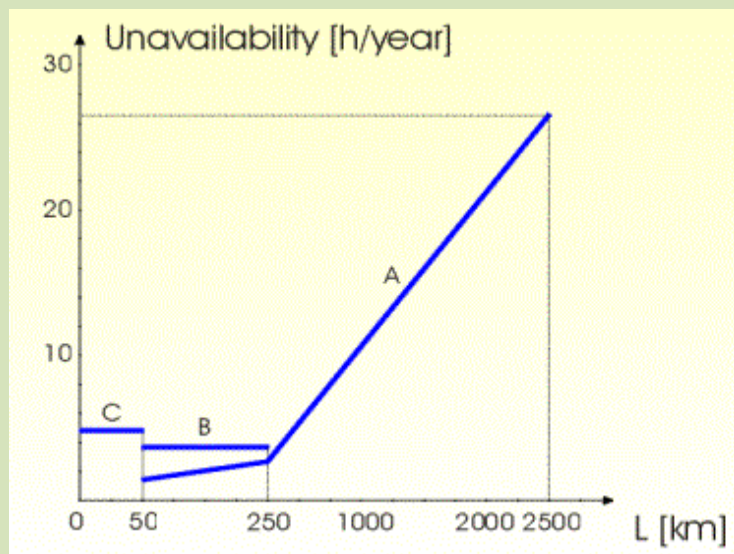
- Network design / planning: both mean and worst-case objectives are appropriate;
- Operational objectives: worst-case objectives are appropriate and are applicable to each individual path.

Radio Link Availability Objectives

In applying the most recent ITU-T availability recs to radio links, the following points have been taken into account:

- Radio propagation models allow to evaluate worst-case performance predictions. So, ITU-R recommends worst-case objectives only and the mean-value objectives, as given by ITU-T G.827, are not considered.
- If availability objectives for radio systems were scaled from ITU-T Rec. G.827, then previous ITU-R objectives would be relaxed in some measure. Therefore, it was decided to be coherent with previous (more stringent) figures, even in the context of new recs.

Unavailability objectives for National links (in the long-haul, short-haul, and access networks), as recommended by ITU-R Rec. F.1493, are shown in the figure below (instead of the UR parameter, the objective is expressed in hours per year).



Unavailability objective (Rec. F.1397).A) Long-haul sections. B) Short-haul sections.C) Access sections.

The Outage Intensity (OI) objective is reported in the Table below (in long-haul sections, the objective for length between 250 and 2500 km can be computed by linear interpolation of the values in the table).

Section	Length	OI [events/year]
	[km]	
Long-haul	250	65
	2500	155
Short-haul		100
Access		120

F.1493 outage intensity (OI) objectives.

Unavailability objectives for International links are given by ITU-R Rec. F.1492 and are the same as for long-haul networks in the national portion (see the previous figure and table).

For practical application of availability objectives, two points have to be considered:

- availability objectives should be partitioned in order to take into account unavailability events due to propagation, equipment failures, human interventions and other causes;
- for the case when the radio link is composed of more than one hop, the objectives are applicable for the whole link. The scaling of objectives to each individual hop is under the network operator responsibility.

Objectives vs. Propagation impairments

Finally, we try to identify how propagation impairments, discussed in previous sessions, may affect the compliance with performance objectives.

The Table below indicates the expected duration of system degradation, caused by various propagation events. Based on degradation period, the relevant performance objective is identify.

Propagation Impairment	Degradation Period	Performance Objective
<ul style="list-style-type: none">• Multipath Fading• Short Term Uncorrelated Interf.	< 10 seconds	Error Performance (SESR)
<ul style="list-style-type: none">• Rain• Obstruction Fading (Sub-Refractivity)• Interference (Super-Refractivity)	≥ 10 seconds	Availability
<ul style="list-style-type: none">• Long Term Correlated Interf.	Permanent	Error Performance (ESR and BBER)

Relation between propagation impairments and applicable performance objectives.

This classification, even if it is rather rough, is quite useful to have practical objectives in the system design stage, so that we can compare performance predictions based on propagation models to objectives set by ITU Recs.

In the most simplifying terms, referring to the main propagation impairments, rain outage predictions will be compared to unavailability objectives, while multipath outage predictions will be compared to error performance (quality) objectives.

This concludes Section 8 of the PPRLE. Please proceed to Herald Lab Exercise 8.

End of Section #8

HERALD LAB

Working with HERALD Lab

The HERALD Lab has been included in this Course with two objectives :

- as a complement of the "Course Notes" presentation, showing you how the propagation concepts and engineering rules are applied in practical cases;
- as an introduction to HERALD functions and commands.

So, working with the HERALD Lab, you should improve both your understanding of radio link engineering and your skills in using the HERALD program.

Each Session in the HERALD Lab starts with the "HERALD Functions" section. It briefly explains how design rules, presented in the Course Notes, are implemented in the HERALD program. This section does not substitute the HERALD Help, where you find a more detailed guide to the program use.

The HERALD Lab Session continues with exercises. Each exercise provides detailed instructions on program steps to execute a given task. Some exercises (in particular in the first sessions) may appear rather easy and even tedious. However, we suggest to skip them only if you already have a good practice in HERALD use.

Using the HERALD program

The exercises proposed in the HERALD Lab require that the HERALD program be installed on your computer. You find the installation program in your CD-ROM, together with installation instructions.

Otherwise, if you receive the course material through e-mail delivery, you can download the HERALD Demo program from by registering at the following link:

http://www.activeonline.com.au/products/hp_register.php

Herald Demo provides all the features required to complete the Herald Lab exercise.

Run HERALD and execute the exercises suggested in the various HERALD Lab Sessions.

As far as possible, do not modify or delete items in the Antenna and Equipment Libraries included in the Herald installation. Some exercise will require the use of specific antenna and/or radio equipment and it is assumed you've got them in your libraries.

For any problem during program execution, first refer to the Herald Help. Remember that, at any stage during program execution, the F1 key gives access to the Help page relevant to the function you're working on.

Otherwise, refer to the PPRLE tutoring service, which is available at <mailto:course@radioengineering.it>.

For general information about the HERALD program, please <mailto:Info@radioengineering.it>

Instructions to HERALD Demo Users

The free Demo Release of the HERALD program includes some functional limitations, which do not impede the use of the program as a training tool in the context of the HERALD Lab activities. In particular:

- Save and Print commands are not supported;
- Open command enabled for example projects only;
- Working frequency limited to 4, 11, 15, 22, 38 GHz;
- No more than 4 radio hops;
- No more than 6 radio sites, with pre-determined names.

HERALD Lab #1 - Hop Configuration

HERALD Functions

The following Herald functions are related to the Hop Configuration process :

- Radio Equipment, Antenna, and Feeder data are stored in customized Libraries (DataBase menu);
- Radio Sites are defined by specifying the site name, elevation a.s.l. and (optionally) geographical coordinates (Define / Sites command);
- Radio Hops are defined by specifying the terminal radio sites, the working (average) frequency, and the hop length (automatically computed, if site coordinates are available) (Define / Hops command);
- Radio Hops are configured by specifying codes and data referring to equipment installation at each radio site, as well as information on link characteristics (use of RF channels, use of passive repeaters, etc.) (Define / Hop Configuration command).

Exercise 1.1 : Radio Equipment data



Run Herald; in the "Getting Started ..." Splash Screen click the New Project icon and skip the two introductory boxes, setting default options. Close the "Radio Sites" dialog, Click the DataBase menu and execute the Equipments command.

- Browse the complete Equipment list (all the Filtering Criteria blank), and examine the main parameters of the selected item; get more details with the "More" button.
- Set the Filtering criteria to find out:
 1. the equipment working at 15 GHz, with 8 Mb/s capacity;
 2. the equipment at any frequency, with about 26 dBm output power;
 3. refine previous selection, with 11 GHz working frequency and 34 Mb/s capacity.

- Add a new equipment, with the following parameters:

Code : So/11/34_bis;

Manufacturer : So-and-So Eln.;

Modulation : 4PSK;

Capacity : 34 Mb/s

RF band : 10.7 - 12.2 GHz

Tx Power : 28 dBm;

Rx Threshold : -79 dBm.

Optional parameters are left blank.

 Tip :

Select one equipment with similar parameters, then click the "Add" button; set a new Equipment Code, modify parameters where required.

- Similarly, practice with the "Modify" and "Delete" functions.

Exercise 1.2 : Antenna data



Run Herald; in the "Getting Started ..." Splash Screen click the New Project icon and skip the two introductory boxes, setting default options. Close the "Radio Sites" dialog, Click the DataBase menu and execute the Antennas command.

- Browse the complete Antenna list (all the Filtering Criteria blank), and examine the parameters of the selected item.
- Set the Filtering criteria to find out:
 1. the antenna at 15 GHz, with about 44 dB gain;
 2. refine previous selection, to be restricted to "Beta Antennas" manufacturer;
 3. any antenna of the "Cassegrain" kind.

- Add a new antenna, with the following parameters:

Code : GamY40-23/D;

Manufacturer : Gamma Antennas;

Kind : Parabolic;

RF band : 21.2 - 24.1 GHz

Polarization : Double;

Application Type : Directive;

Diameter : 0.40 m;

Gain : 35.8 dB;

3-dB BeamWidth : 2° 30'

Optional parameters are left blank.



Tip :

Select one antenna with similar parameters, then click the "Add" button; set a new Antenna Code, modify parameters where required.

- Similarly, practice with the "Modify" and "Delete" functions.

Exercise 1.3 : Feeder data



Run Herald; in the "Getting Started ..." Splash Screen click the New Project icon and skip the two introductory boxes, setting default options. Close the "Radio Sites" dialog, Click the DataBase menu and execute the Feeders command.

Similarly to the previous exercises, browse the complete Feeder list, set the Filtering criteria, and practice with the "Add", "Modify", and "Delete" functions.

Exercise 1.4 : Site & Hop definition

 Tip :



Radio network topology definition is assisted by the two Herald icon:

Define / Sites command



Define / Hops command



 Run Herald; in the Getting Started screen, click the  icon "Start a New Project - Radio Site definition". Confirm default options in the two introductory dialogs "New Project - Default settings" and "Set Coordinate System", Then the "Radio Sites" dialog box will be displayed.

- Click the "Import from ASCII file" button, then select Sites_1.txt file in the "Open File" dialog. The coordinates of three radio sites (ALPHA, BETA, and CHARLIE) will be imported.
- Alternatively, use the "Create" button to display the "New Site Data" dialog box, where you can define the same radio sites:

Site Code	Elev. [m]	Latitude	Longitude
ALPHA	392	N 45° 14' 25.0"	E 7° 31' 52.0"
BETA	238	N 45° 03' 42.0"	E 7° 42' 15.0"
CHARLIE	529	N 45° 00' 12"	E 7° 40' 25"

- Practice with the "Modify" and "Delete" functions; then close the dialog box using the "Close" button.
- Execute the Define / Hops command to display the "Radio Hops" dialog box. Use the "Create" button to display the "Radio Hop Data" dialog box, where you define the following hops:

Hop Code	Frequency	Length
ALPHA-BETA	11 GHz	as computed
ALFA -CHARLIE	15 GHz	as computed
BETA -DELTA	38 GHz	2.5 km

The DELTA site is not yet defined; use the "Add Site" button ("Radio Hop Data" dialog box) to define a New Radio Site at this stage (DELTA site elevation is 288 m, geographical coordinates not available).

- Use the "Report" button (in the "Radio Hops" dialog box) to display the Hop Report; do not care about Warning message (Antenna not defined, Link budget not computed: the new hops are defined only topologically, the hop configuration will be defined in the next exercise).
- Execute the File / Save command to save this project, with name "Config1.hpf" (if your HERALD release does not support the "Save" function, don't worry; you'll find the "Config1_Sample.hpf" file in your Project examples).

Exercise 1.5 : Hop configuration



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Config1.hpf" or Config1_Sample.hpf" project (or find it in the Recent Projects list). The open project is the one you've created in the [previous exercise](#)). The "Radio Hops" dialog box is displayed.

- Select the ALPHA-BETA hop, then use the "Config / Modify" button to display the "Hop Configuration" dialog box.
- Configure the ALPHA site by using the three "Select" buttons (Main Antenna, Feeder, Equipment); fill the Antenna Height, Feeder Length and Branching Loss fields; do not check the Diversity Antenna box.
- Similarly, configure the BETA site; note that some data are copied by default from the first site selections; use the "OK" button to save the new configuration and to get the Hop Report (at the moment, consider only the Configuration section of the Report).
- Practice with the "Hop Configuration" dialog: revise the ALPHA-BETA configuration (including a diversity antenna) and configure the other two hops.



Tips :

To revise the Active Hop configuration, click the Herald icon:



Define / Hop Configuration command 

To set a new Active Hop, execute the Define / Hops command, then use the "Config / Modify" or the "Report" buttons. The Active Hop is indicated in the Status Bar.

- In the "Hop Configuration" dialog, complete the Hop Configuration, using the "Losses/Degrad. Define" button (Radio Site frame) and the "Propagation Losses Define" button (Radio Hop frame); the "Various Losses" dialog is displayed, where you can set several parameters, related to the radio transmitter and receiver structure and to propagation conditions.
- When appropriate, execute the File / Save command to update the project; use a different project name (File / Save As command) if you want to save several versions of your project.

Exercise 1.6 : Passive repeater



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Config2_Sample.hpf" project (or find it in the Recent Projects list). Close the "Radio Hops" dialog. Execute the Define / Sites command to display the "Radio Sites" dialog box ( Tip : Use the Herald icon )

- Use the "Create" button to display the "New Site Data" dialog box, where you define the repeater site :

Site Code	Elev. [m]	Latitude	Longitude
ZEBRA	617	N 45° 14' 52.0"	E 7° 29' 52.0"

Set the "Repeater Site" checkbox in the same dialog, then Close the dialog.

- Select the ALPHA-CHARLIE hop, then use the "Config / Modify" button to display the "Hop Configuration" dialog box. Complete Hop Configuration as for the ALPHA-BETA hop in the previous exercise.
- While you're still in the "Hop Configuration" dialog box, click the "Passive Repeater / Define" button, select the "Single Plane Reflector" option, then define the passive repeater parameters :

Site code : ZEBRA;

Reflector area : 25 m²;

Reflector Vertical dim. : 4 m;

Installation Height : 25 m.

- The "Path profile" dialogs appear for each of the two legs in the repeater hop. It is possible to read/define the path profiles at this stage, but we suggest you close the two dialogs without any new data.
- In the "Hop Configuration" dialog, use the "OK" button to save the new configuration and to get the Hop Report (consider only the Configuration section of the Report). Find the Repeater Site section and check the Topology and Reflector parameters.
- Execute the File / Save command to save this project (radio hop with passive repeater).

Exercise 1.7 : Export Network Topology to Google Earth

Note: You need to have Google Earth installed in you PC to execute this exercise.



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Config2_Sample.hpf" project (or find it in the Recent Projects list). Close the "Radio Hops" dialog box.

- Execute the File / Export Network to Google Earth command. Click YES in the box asking for saving a kml file (call it Config2).
- Click YES in the next box asking if you want Google Earth to be executed immediately. Radio sites and radio hops are displayed in a Google view. A summary of Network data are listed in the Google data frame on the left (if activated).
- Tune Google Earth display zoom and other properties as you prefer. Click on the radio site icon to read site coordinates and elevation. Similarly, click on the hop line to read hop length and frequency

Exercise 1.8 : Import Radio Sites



Run Herald; in the "Getting Started ..." Splash Screen click the New Project icon. Skip the two introductory boxes, setting default options. Then the "Radio Sites" dialog box is displayed.

- Click the "Import from Google (*.kml) File" button; then, in the "Open File" dialog, select the Config2.kml file saved in the previous exercise.
- The Radio Sites in Config2 are listed in the "Radio Sites" dialog..

End of HERALD Lab#1

HERALD Lab #2 - Link Budget and Fade Margin

HERALD Functions

Each time the Hop Report is displayed, an updated Link Budget is computed. The Link Budget is displayed and can be printed. It leads to the evaluation of the Hop Fade Margin.

Exercise 2.1 : Compute Link Budget



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "LBudget1_Sample.hpf" project (or find it in the Recent Projects list).

- In the "Radio Hops" dialog, select the ALPHA-BETA hop and click the "Config / Modify" button to display the "Hop Configuration" dialog; check how the sites and hop are presently configured; click the "OK" button to display the Hop Report; check the Configuration section of the Hop Report; check the Link Budget (in the Performance section of the Hop Report).
- Return to the "Hop Configuration" dialog and complete the Hop Configuration, using the "Propagation Losses Define" button (Radio Hop frame); the "Various Losses" dialog is displayed, where you can set several loss and degradation parameters, related to the radio transmitter and receiver structure and to propagation conditions.
- Compute again the Link Budget and examine the Propagation losses section; practice with the iterative process of revising configuration / checking link budget.
- Complete the Configuration and compute the Link Budget of other hops in the "LBudget1_Sample.hpf" project.

Exercise 2.2 : Adjust Fade Margin



Run Herald as in the previous exercise.

- Select the ALPHA-BETA hop and revise the site configuration (Antenna and Equipment selection) to obtain a Fade Margin approximately equal to 40 dB, with a 140 Mb/s or STM1 capacity; find at least two alternative solutions.



Tip :

Set a tentative configuration, check the link budget and take note how much the fade margin target is missed. Go back to Hop Configuration, modify the Antenna and/or Equipment selection in order to adjust appropriately gain / Tx power / Rx threshold (browse the Antenna and Equipment libraries); use Tx or Rx attenuators ("Losses/Degrad. Define" button) if necessary.

- Comment on the alternative solutions you've found to the above problem.



Tip :

Main factors in comparing the antenna / equipment configurations are :

- Antenna installation problems;
 - Emitted power, antenna directivity (interference produced / received)
 - Overall cost (antenna, equipment).
-
- Repeat the above for the other hops :

BETA-CHARLIE, 34 Mb/s capacity, fade margin objective 48 dB;

BETA-DELTA, 2 Mb/s capacity, fade margin objective 48 dB.

Find the maximum fade margin achievable using the existing antenna / equipment libraries.
-
- Sample projects close to the above objectives are given in "LBudget2_Sample.hpf" (note that propagation losses to be considered in the "Hop Configuration" dialog will be discussed in later sessions)

Exercise 2.3 : Print Hop Report



Run Herald as in the previous exercises, select one hop and display the Hop Report.



Tip :

Alternative ways to display the Hop Report are :

- Execute the "Define / Hops " command, select the desired hop, then click the Report button (the selected hop is set as the Active Hop);
- Execute the "Display / Hop Report" command: you get the Hop Report referring to the presently set Active Hop (shortcut: CTRL + H);
- Execute the "Define / Active Hop Configuration" command, in the "Hop Configuration" dialog revise the site/Hop configuration (if necessary), then click the "OK" button.
- Arrange settings related to output documents: Language (Customize / Language command) and Project information (File / Project Info command).
- Execute the File / Print command (if this command is not supported in your HERALD release, you can anyway check the print result using the File / Print Preview command);

Exercise 2.4 : Include a Passive Repeater



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "LBudget3_Sample.hpf" project (or find it in the Recent Projects list). The open project is the one produced in the Hop Configuration Exercise 1.6).

- Select the ALPHA-BETA hop and click the "Config / Modify" button to display the "Hop Configuration" dialog. Click the "Passive Repeater / Define" button and check the passive repeater configuration parameters (single reflector). Do not modify reflector parameters; do not define path profiles (not considered at this stage).
- Close the "Hop Configuration" dialog with the "OK" button so the Hop Report is displayed. Check the Topology and Reflector parameters in the "Configuration / Repeater Site" section of the Report and the link budget results in the "Performance / Repeater Loss" section.
- Return to the "Hop Configuration" / "Passive Repeater" dialogs and modify the reflector size; check the Repeater Loss in the Hop Report. Note the dependence of repeater loss on reflector size (6dB reduction if size is doubled). Set again the reflector size to 25 m².
- Move the ZEBRA (repeater) site position closer to the ALPHA site (Define / Sites command). Set the same longitude of the ALPHA site (E 7°31'52"), do not modify latitude. Note that the ALPHA-ZEBRA distance is 0.83 km only. In the Hop Report, note that a "Near field correction" in the Repeater Loss is included (1.1 dB).
- With the new ZEBRA position, reduce the reflector size to 16 m². In the Hop Report, note that the "Repeater Basic Loss" increases (reduced effective area), while the "Near-field Correction" decreases (see parameters α , β used to estimate Near-field correction) . Similarly, select a smaller (2 m) antenna at the ALPHA site; the near-field correction is reduced (larger antenna mainlobe, smaller β parameter).

End of HERALD Lab#2

HERALD Lab #3 – Path Clearance

HERALD Functions

The following Herald functions are related to Profile analysis, clearance criteria, and obstruction loss estimation :

- The path profile is specified as a set of points (distance from first site, ground elevation above sea level, and obstruction above ground level, if any). It can be defined (or modified) using the Define / Path Profile command (manual data editing; import from table in ASCII format; import from NASA/SRTM digital elevation maps); also in the "Hop Configuration" dialog, the Hop Length / Profile button gives access to the profile definition dialog.
- Clearance criteria are set using the Evaluate / Clearance / Criteria command. Two (median and minimum) k-factor values are set; for each k-factor value, the percentage of the Fresnel ellipsoid, that is required to be free from any obstruction, is specified; data derived from ITU-R Rec. P-530 are set as a default (including the minimum k-factor value, computed as a function of path length).
- The path profile is displayed using the Display / Path Profile command; if clearance criteria are not yet set, only the terrain profile is shown, with radio site data; otherwise, two Fresnel ellipsoids, for given radius percentages, are plotted (see the blue and green lines in the example given in the Course Notes).
- The path profile view is completed with a table, where results on normalized clearance and margins are displayed; indication about compliance with clearance criteria and estimate of obstruction loss are reported below the table.
- The antenna height definition is part of the "Hop Configuration" dialog; the antenna height can be modified also by means of the Evaluate / Clearance / Antenna Height command. Tentative values of antenna height can be set and compared with the previous ones.
- The Evaluate / Clearance / Obstruction Loss command displays a dialog where the estimates of the obstruction loss are given for the three obstacle models indicated by ITU-R Rec. P-530 (knife-edge, smooth spherical earth, intermediate terrain); it is assumed that the operator enters the final estimate of the Obstruction Loss.

Exercise 3.1 : Define path profile



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "LBudget2_Sample.hpf" project (or find it in the Recent Projects list). The open project is the one produced in exercises in [Herald Lab #1](#) and [Herald Lab #2](#).

- Select the ALPHA-BETA hop and check the Hop Configuration; if the antenna height was not selected previously, set 25 m at the ALPHA site and 20 m at the BETA site.
- Execute the Define / Profile command; in the "Path Profile" dialog, click the "Read Points from ASCII file" button and load the "Profile.txt" file. Check the profile table, where profile points should be :

Distance from first site [km]	Terrain elevation [m]	Obstacle above terrain [m]
1	375	0
5	366	0
11.5	280	0
20	245	0

- Test the alternative import function: in the "Path Profile" dialog click the "Read Profile from SRTM Maps". Check the profile table with more detailed data.
- Close the "Path Profile" dialog and check the profile displayed; practice with the profile definition process, by adding and deleting points; at the end, take care to set the profile according to the table above.



Tip :

Use the Herald icon:

Define / Hop Configuration command



Define / Path Profile command



Display / Path Profile command



Exercise 3.2 : Check clearance




Run Herald and ; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Clearance1_Sample.hpf" project (or find it in the Recent Projects list). In the "Radio Hops" dialog select the ALPHA-BETA hop and display the path profile.

- Execute the Evaluate / Clearance / Criteria command to display the "Planning Criteria for Path Clearance" dialog. In the upper frame, check that the Relevant factors are correctly set: frequency above 2 GHz, Temperate climate (as indicated by radio site coordinates), single obstruction; then, in the lower frame, the ITU-R criteria are set as a default; check the standard and minimum values of the k-factor and the corresponding Fresnel radius percentages (compare with [minimum k-factor diagram](#) and the [chart of ITU-R clearance criteria](#)); note how the criteria modify if you change the settings in the upper frame.
- Click the OK button to display the path profile with Fresnel ellipsoid margins for given percentages ([blue and green lines](#)); examine the table above the diagram, with indication of the assumptions relevant to the blue and green curves and the results on normalized clearance and margin.
- Return to the "Planning Criteria for Path Clearance" dialog;



Tip :

Use the Herald icon . Set clearance criteria different from the ITU-R default. Take note of the result in the path profile diagram.



Tip :

You can set the k-factor and the F1 percentage in order to display ray trajectories or Fresnel ellipsoids of your interest. For example, with a given k-factor, if you set the Fresnel Radius % to zero, then the line in the diagram is the ray trajectory for that k-factor value; if you set 100%, then the line displayed is the lower margin of the full Fresnel ellipsoid..

- When the profile and Fresnel ellipsoid diagram is displayed, move your mouse along the path profile and click the left button: a path position is selected, where clearance parameters are computed. The "Profile Check Point" dialog is displayed, where you have options to save that point and/or display results in the profile diagram table.

Exercise 3.3 : Modify antenna height




Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Clearance1_Sample.hpf" project (or find it in the Recent Projects list). In the "Radio Hops" dialog select the ALPHA-BETA hop.

- Display the path profile and set the k-factor and Fresnel radius percentages to the correct values, as discussed in the previous exercise; then execute the Evaluate / Clearance / Antenna Height command



Tip :


Use the Herald icon . In the "Antenna Height Definition" dialog, modify the antenna height values and check the new results.

- Again, in the "Antenna Height Definition" dialog, set Tentative values and check the "Plot Tentative Values" checkbox. In the profile diagram, you see the Fresnel ellipsoid sections, both with the previous antenna height values and with the tentative ones; compare the results with the two options of antenna height (note that the red line refers to same (k, %) condition as the blue line; similarly, the gray line compares with the green one).
- Execute the Evaluate / Clearance / Antenna Height command; if you set ON the "Tentative → Design" checkbox, then tentative values are assigned as antenna height design values; if you uncheck the "Plot Tentative Values" checkbox, then the antenna height values are unchanged.
- When you modify the antenna height, the indications below the table in the profile diagram are updated. Note that :
 - a. the "Clearance criteria (NOT) satisfied" label depends on the Margin values: only if both margins (referring to standard and minimum k-factor) are positive, then criteria ARE satisfied;
 - b. the Obstruction Loss estimate is set to "0 dB" as long as the Normalized Clearance for standard k-factor is > 0.5 (see [diagram](#)). So, it may happen that clearance criteria are not satisfied even if the estimated obstruction loss is zero. To explain this, consider that : (i) clearance criteria require some margin; (ii) clearance criteria apply both to standard and minimum k-factor, while obstruction loss is estimated for standard k-factor.

Exercise 3.4 : Estimate obstruction loss







Go on with the same project as in the previous exercise. Select the ALPHA-BETA hop and display the profile and Fresnel ellipsoid diagram.

- With 25m and 20m antenna height at ALPHA and BETA sites respectively, the line below the table will read "Clearance Criteria satisfied - Estimated Obstruction Loss = 0 dB"
- Modify (reduce) the antenna height so that the "Click here to estimate Obstruction Loss" label appears below the table.
- Click on the above mentioned line (or execute the Evaluate / Clearance / Obstruction Loss command); the "Obstruction Loss Estimate" dialog is displayed, with the results referred to the three obstacle models (knife-edge, smooth spherical earth, and intermediate terrain) and to the rounded obstacle model, as in ITU-R Recommendations. Note that the operator enters the final estimate of the Obstruction Loss. In this case, the "Rounded obstacle" value can be a reasonable choice.
- Execute the Display / Hop Report command ( Tip : Use the shortcut: CTRL + H). Check the Link Budget, where the previously set Obstruction Loss must be included.

Exercise 3.5 : Display Profile Report



Continue with the "Clearance1_Sample.hpf" project, as revised in previous exercises :

- Select the ALPHA-BETA hop, then execute the Display / Profile Report command; check the Profile point list and results of clearance analysis (do not consider warnings about reflection analysis).
- Display the Path Profile ( Tip : click the  icon). Then, click the mouse along the path profile, to add points to the "Check Point" list (in the "Profile Check Point" dialog, set to ON the checkbox "Add to check point list").
- Execute the Define / Path Profile command ( Tip : click the  icon) to display the "Path profile" dialog, where you can find the selected check points added to the profile points. Delete undesired points (if any).
- Again, display the Profile Report and verify that the Profile Check Points are listed (for those points, the elevation is the result of linear interpolation and is written in brackets).

End of HERALD Lab #3

HERALD Lab #4 – Ground Reflections

HERALD Functions

The following Herald functions are related to Reflection analysis :

- The Evaluate / Reflections / Plot All command displays the Path Profile and plots all the (geometrically possible) reflection points, even if partially obstructed. The operator is enabled to select a single reflection, to be analyzed in details; the relevant geometrical and radio parameters are presented in the table above the profile diagram.
- After a reflection point has been selected on the profile diagram (reflected rays plotted in red), the Evaluate / Reflections / Analyze command can be used to display the "Reflection Analysis" dialog. In the upper frame, the operator sets the relevant parameters (reflection coefficient, use of diversity and antenna spacing). In the second frame the results are shown, with details on the Reflection Path Losses (Antenna directivity, Obstruction Loss in the Reflection Paths, Reflection Coefficient, and Divergence Factor), reflection delay and grazing angle. In the lower frame some Notes may appear when critical parameters are estimated.
- The "Rx Power vs. k" button, in the "Reflection Analysis" dialog, displays a diagram where the received power is plotted as a function of the k-factor, at the main and at the diversity (if configured) antennas.
- The "Antenna Height" button, in the "Reflection Analysis" dialog, displays the "Antenna Height" dialog, where antenna height can be modified.
- The "OK - Store results" button, in the "Reflection Analysis" dialog, saves the Reflection Analysis results. Note that the Rx threshold degradation (single and diversity reception, if configured) is estimated, while the operator can enter the final degradation result (to be included in the Link Budget), taking account of some conservative margin, if necessary.


Exercise 4.1 : Estimate reflection parameters



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Reflection1_Sample.hpf" project (or find it in the Recent Projects list). This project is already initialized (4 GHz, 60 km over-the-sea radio hop with reflection).

- Select the ALPHA-BETA hop and execute the Evaluate / Reflections / Plot All command.



Tip : Use the Herald icon 

- The reflection point at 30.9 km should be selected. If another reflection point is selected, change selection by pressing the Tab key
- Examine the Reflection parameters; in particular note that:
 - a. the path difference is 78 cm, much greater than the signal wavelength (7.5 cm at 4 GHz);
 - b. the time delay is 2.6 ns, much shorter than the symbol period in any digital modulation;
 - c. the direct-to-reflected ray angles, at both terminals are very small, so the loss in antenna gain is almost negligible (0.3 dB);
 - d. the reflected ray path is clear (no obstruction loss).
- By pressing the Tab key, select the other reflection point (at about 5.4 km); this reflection is probably NOT significant, it derives from approximations made in the path profile, describing the steep terrain close to the radio site; note, in this case, a substantial loss in antenna gain (6 dB) and a partial obstruction of the reflected ray.

Exercise 4.2 : Analyze Rx power level

Go on with the "Reflection1_Sample.hpf" project, as in the previous exercise.

- Execute the Evaluate / Reflections / Plot All command, then select the reflection point at 30.9 km (use the Tab key, if necessary).
- Execute the Evaluate / Reflections / Analyze command. In the "Reflection analysis" dialog, first consider the "SET PARAMETERS" frame; set the Reflection coefficient to 0 dB, and uncheck the two Diversity checkboxes
- Examine the "RESULTS" frame; note the Total Loss in the reflection path, with all the items that contribute to the final result. Take note of the Rx degradation estimate.
- Click the "Rx Power vs. k" button to get the diagram of received power as a function of k-factor. Note that a small change in the k-factor around the standard value (1.33) causes the Rx power to change significantly. Return to the "Reflection analysis" dialog.

Exercise 4.3 : Design diversity Rx

Go on with the "Reflection1_Sample.hpf" project, as in the previous exercise. Display the "Reflection analysis" dialog.

- Enable the Diversity checkboxes (upper frame), set the antenna spacing to optimum values (Optimum Diversity button) and repeat the steps indicated at the previous point.
- The Rx degradation with diversity is 0 dB. Display the Rx power vs. k diagram and verify that the two curves are well interleaved (not overlapping). For any k-factor value, one of the two antennas receives a signal at a high power level: diversity reception is quite effective (however, consider that 0 dB degradation is computed under the assumption of an ideal diversity switching).
- Return to the "Reflection analysis" dialog and set the antenna spacing at Site ALPHA at 12 m; note that the Rx degradation (with diversity) is increased to 1.8 dB. In the Rx power vs. k diagram, the two curves at site ALPHA are not well interleaved and overlap for $k > 1.5$; this is an example of INEFFECTIVE diversity design.
- Complete your design with optimum diversity spacing and a final estimate of Rx degradation. This may be a 1 dB degradation, since the 0 dB estimate is computed under the assumption of an ideal diversity switching and the Single Rx degradation is estimated 3.9 dB. Set the final estimate in the "Assumed in Link Budget" data cell. Press the "OK - Store results" button to exit, then check that the results are included in the Hop Report and in the Profile Report.

Exercise 4.4 : Change reflection parameters



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Reflection1_Sample.hpf" project (or find it in the Recent Projects list). In the "Radio Hops" dialog select the ALPHA-BETA hop and display the Path Profile with reflection rays. Starting from this state, you have several ways of changing the radioelectrical and/or geometrical parameters in the reflection path. Below are some examples; in each condition, take note of new aspects of reflection analysis.

- Execute the Evaluate / Reflections / Analyze command. In the "Reflection analysis" dialog, modify the Reflection coefficient to 3, 6, or 10 dB. Take note of new results with increasing attenuation of the reflected ray.
- In the Path Profile diagram, select the reflection point at 5.4 km. Repeat all the main steps in previous analysis, assuming a 3 dB reflection coefficient (quite conservative for reflection on dry soil or rocks). Note the role of antenna directivity in increasing the reflection path loss.
- Execute the Evaluate / Reflections / Analyze command. In the "Reflection analysis" dialog, press the "Antenna Height" button and revise the project with different antenna heights.

Exercise 4.5 : Move radio site position



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Reflection1_Sample.hpf" project (or find it in the Recent Projects list). In the "Radio Hops" dialog select the ALPHA-BETA hop and display the Path Profile with reflection rays.

- Execute the Define / Path Profile command and modify the Hop Length from 59.5 to about 62.0 km;

this means that BETA has been moved some 2.5 km far from the coastline.

- Close the "Path Profile" dialog; then execute the Reflections / Plot All command. The new BETA position produces a partial obstruction in the reflected ray, with a substantial signal loss (see reflection data in the table above the profile diagram).
- Check Path Clearance with the new BETA site position (see [HERALD Lab #3](#)). It appears that clearance criteria are not satisfied. Increase by some 2-4 m the antenna height at the BETA site, so that path clearance is confirmed. Check again the reflection results (the obstruction loss in the reflected signal is slightly lower, but still useful).
- Execute the Reflections / Analyze command and revise the results with the additional attenuation in the reflected signal. This is an example of the significant benefit offered by a "lucky" positioning of the radio site (unfortunately, hop design is not always so easy as in computer examples ...).

End of HERALD Lab #4

HERALD Lab #5 – Multipath Fading

HERALD Functions

The following Herald functions are related to Multipath analysis :

- The Evaluate / Multipath command displays the "Multipath Occurrence Model" dialog, where the operator sets the parameters useful to estimate the Multipath Occurrence Factor P_0 , according to the selected model. (Note: if the "Multipath Outage" dialog is displayed, then click the "Revise P_0 estimate" button to return to the "Multipath Occurrence Model" dialog).
- Using the Barnett-Vigants model, the required parameters are the climatic region (to be selected among the five regions proposed by that model) and the path roughness (if the path profile is defined, then the roughness is automatically computed). The model is also based on the path length and operating frequency (both are already defined at this design stage).
- After definition of model parameters, the Multipath Occurrence Statistics diagram is displayed. Note that the statistics diagram is plotted, according to ITU-R Rec. P-530, with time percentages as the abscissa axis and fade depth as the ordinate axis. The low attenuation region (approximately, for fade depth lower than 15 dB) deviates from the 10 dB / decade slope, according to Rec. P-530 (sect. 2.3.2) formulas for "shallow-fading".
- Once the Multipath Occurrence Factor P_0 has been estimated, the Evaluate / Multipath command displays the "Multipath Outage" dialog. After parameter setting, click OK to display the Outage diagram; on the right of the diagram, the available Flat Fade Margin and the outage prediction (in time percentage and seconds in the worst month) are given.
- In order to define a space diversity receiver configuration, the Define / Active Hop Config command must be executed to display the "Hop Configuration" dialog, where the option for a diversity antenna can be set at one or both receiver sites. Space diversity is completed by selecting the antenna code(s) and the antenna spacing.
- Both the Multipath Occurrence Statistics and the Multipath Outage diagrams take account of space diversity, when configured.

- In the Hop Report (Configuration section) the "Environmental Parameters and Propagation Models" lines indicate the assumptions on Multipath analysis, while at the end of the Performance section the predicted outage (single Rx and diversity Rx, if configured) is reported.

Exercise 5.1: Estimate multipath occurrence



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Multipath1_Sample.hpf" project (or find it in the Recent Projects list).

- In the "Radio Hops" dialog select the DELTA-ECHO hop (11 GHz, 48 km) and display the Hop Report. Check that no reference to multipath analysis is reported in the Configuration or in the Performance sections of the Hop Report.
- Execute the Evaluate / Multipath command.
- In the "Multipath Occurrence Model" dialog, you have to set the Barnett-Vigants model parameters. The profile roughness is already computed (10 m) from the terrain profile previously defined. Test how the selection of the Climatic Region affects the Occurrence Factor P_0 , shown in the same dialog. Finally, select the "Continental temperate" region. Click the OK button.
- The Multipath Occurrence Statistics diagram is displayed. Note the deep fading region (10 dB / decade slope) and the shallow-fading region (low attenuation). Click the Exit button (right-bottom corner of the screen).
- After initialization of multipath analysis, save the project as "Multipath2.hpf" (if your HERALD release does not support the "Save" function, don't worry; you'll find the "Multipath2_Sample.hpf" file in your Project examples).
- To test how the profile roughness affect the Multipath Occurrence Factor, delete the path profile (Define / Profile command, then delete all points). In the "Multipath Occurrence Model" dialog, you can now modify the Profile Roughness parameter (the acceptable range in the Barnett model is 6 to 42 m).

Exercise 5.2: Estimate multipath outage



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Multipath2.hpf" (or the "Multipath2_Sample.hpf") project, as revised in the previous exercise. In the "Radio Hops" dialog select the DELTA-ECHO hop.

- Execute the Evaluate / Multipath command. The "Multipath Outage" dialog is displayed; do not check any checkbox nor set any plotting comparison. Click the OK button.
- The Multipath Outage diagram is displayed; on the right you find a summary of the hop parameters, propagation model, and outage predictions. Note that only the "narrowband" or "non-selective" multipath model is applied in this example.
- Display the Hop Report and find results of multipath analysis at the end of the Performance section.

Exercise 5.3: Frequency selective multipath

Go on with the project carried on in the previous exercise.

- Go to the "Hop Configuration" dialog to select the equipment with code "D/11000a" (signature data are defined). Then repeat the Outage estimation process, using the "frequency selective" multipath model.
- When you execute the Evaluate / Multipath command, in the Multipath Outage dialog, set the Plotting comparison checkbox "Narrow vs. Wide-band (Selective fading)".
- Comment on the results in the Multipath Outage diagram.



Tip :

the outage prediction produced by the Narrowband model is a decreasing function of the Fade Margin. On the other hand, the outage prediction estimated under the Wideband (frequency selective) model has a flat asymptote. This is due to the frequency selective outage component (the outage probability due to signal distortion which cannot be reduced under a given value, even increasing the fade margin).

Exercise 5.4: Design space diversity



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Multipath2.hpf". In the "Radio Hops" dialog select the DELTA-ECHO hop. The predicted outage with single receiver and the Narrowband multipath model is very high (several minutes/month) and probably not acceptable

- Display the "Hop Configuration" dialog (Define / Active Hop Config command) and configure the diversity antenna at both radio sites. Select the same antenna code, used as the main antenna, set the diversity spacing at 180 wavelengths (about 5m), as a tentative value.
- Execute the Evaluate / Multipath command and test the new outage predictions. More complete results are given in the Hop Report (comparison of outage predictions in single and diversity reception, diversity improvement).
- Execute the Evaluate / Multipath command, click the "Revise Po estimate" button to return to the "Multipath Occurrence Model" dialog; click OK to display the Multipath Occurrence Statistics diagram; note that the diversity curve slope (in deep fading region) is 5 dB / decade.
- Repeat the analysis with different antenna spacing and test how the diversity improvement varies.



Tip :

set a different spacing at the two sites, then display the Hop Report, so you can immediately compare the diversity improvements (this is correct as far as the fade margin is the same at the two Rx sites).

Exercise 5.5: Use frequency diversity



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Multipath2.hpf". In the "Radio Hops" dialog select the DELTA-ECHO hop.

- Display the "Hop Configuration" dialog (Define / Active Hop Config command) and click the "Frequency Diversity / Define" button. Select the 1+1 frequency diversity configuration, with 80 MHz channel spacing (this is the co-channel RF spacing in the ITU 11 GHz channel arrangement).
- Close the open dialogs and execute the Evaluate / Multipath command to test the new outage predictions. Set the Plotting Comparison checkbox "With and W/o Frequency diversity"
- Repeat the exercise with a different channel spacing.
- Repeat the exercise with the Wideband (frequency selective) multipath model, as introduced in [Exercise 5.3](#).

End of HERALD Lab #5

HERALD Lab #6 – Rain Attenuation

HERALD Functions

The following Herald functions are related to Rain attenuation :

- The Evaluate / Rain command displays the "Rain Model" dialog, where the operator sets the parameters required to implement the ITU-R rain attenuation model, based on rain intensity statistics.
- The main model parameter is the rain intensity for 0.01% of the time: it can be set directly by the operator; or the [ITU-R rain region](#) can be selected (the rain intensity is automatically set), or the [ITU-R rain database](#) can be accessed, on the basis of hop coordinates.
- The hop coordinates are also required if the most recent version of Rec. 530 is applied, in order to specify if the hop operates in the temperate or in the equatorial/tropical zone (latitude lower than 30°, North or South).
- Other parameters are the Rx signal polarization at each receiver site and the wet radome loss (if any).
- The Rain Unavailability diagram shows the time percentage as a function of the rain attenuation, both for horizontal and vertical polarizations; on the right, the predicted unavailability is reported, taking account of the specified polarization at each Rx site and of the wet radome loss.
- The Hop Report, at the Environmental Parameters & Propagation Models lines (Configuration section), indicates the assumptions made about the rain attenuation model. At the end of the Performance section, the rain unavailability predictions are reported.

Exercise 6.1 : Predict rain unavailability



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Rain1:Sample.hpf".

- In the "Radio Hops" dialog, select the BETA-DELTA hop (38 GHz, 2.5 km) and display the Hop Report

- Execute the Evaluate / Rain command.



Tip :

Click the HERALD icon



- In the "Rain Model" dialog, set the model parameters; to set rain intensity, you can :
 - a. enter directly the desired value,
 - b. select a rain region (ITU-R Rec. 837-2) ,
 - c. click the "DataBase" button to access the ITU-R Rec. 837-3 rain intensity archive.
- The Rain Unavailability diagram is displayed. Note the unavailability prediction for each Rx site, on the right, and the significant difference between the two curves for H-pol. and V-pol.
- Return to the "Rain Model" dialog, to modify the model parameters, and display again the Rain Unavailability diagram.
- Check the results reported in the Hop Report (model parameters in the Configuration section and predicted unavailability in the Performance section).

Exercise 6.2 : Optimize hop design



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Rain1_Sample.hpf". In the "Radio Hops" dialog, select the ECHO-DELTA (22 GHz, 6 km) hop.

- In the "Hop Configuration" dialog, note that the antenna are not selected yet. Make a tentative selection, then display the Hop Report and take note of the available Fade Margin.
- Execute the Evaluate / Rain command. In the "Rain Model" dialog, set the "L" rain region and the H-pol. at both sites. Select the option "Rec. P.530-7", so that operation in the temperate region is assumed (even if hop coordinates are not defined).
- Examine the Unavailability results. Modify antenna selection (return to Hop Configuration), if necessary, to get a rain unavailability objective below 30 min/year.
- Revise the previous design to the objective of minimum cost antennas, with accepted rain unavailability up to 45 min/year.

Exercise 6.3 : Include atmospheric absorption

Go on with the "Rain1_Sample.hpf" project, as updated in the previous exercise. Select the ECHO-DELTA (22 GHz, 6 km) hop.

- Estimate the water vapour specific attenuation at about 22 GHz, for 60% relative vapour density at about 15 °C.
- Display the "Hop Configuration" dialog and click the "Propagation Losses / Define" button. In the "Various Losses" dialog, set the Atmospheric Absorption at the value computed above.
- Close the "Hop Configuration" dialog and check the Fade Margin (reduced by the additional loss).
- Revise the rain unavailability predictions with the reduced fade margin.

Exercise 6.4 : Revise design for tropical regions

Go on with the "Rain1_Sample.hpf" project, as updated in the previous exercise. Select the ECHO-DELTA (22 GHz, 6 km) hop.

- Execute the Evaluate / Rain command. In the "Rain Model" dialog, set parameters for tropical regions:
 - geo coordinates : set (S4°, W40°);
 - rain intensity ; click button "ITU-R Rec. 837-3 DataBase";
 - if the ITU-R DataBase files are not loaded, select the "N" rain region;
 - i) set option "Rec. P.530-8";
 - ii) set V-pol. at both sites, to minimize attenuation.
- Examine the Unavailability results. Modify antenna selection (return to Hop Configuration), if necessary, to get the same objectives as in Exercise 6.2.

Note that the time unavailability diagram has a change of slope, close to 0.001%. In some cases, a few dB's change in fade margin produce a remarkable variation in the predicted unavailability and significant difference between H-pol. and V-pol. results. This may be a weak point in the present model; results in this range must be considered with some care.

Exercise 6.5 : Use Freq./Pol. scaling



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Rain1_Sample.hpf". In the "Radio Hops" dialog, select the BETA-DELTA (38 GHz, 2.5 km) hop.

- Execute the Customize / Propagation model command. In the "Propagation Models" dialog, set the Rain Attenuation model (upper-left frame) to "Frequency / Polarization Scaling"
- Execute the Evaluate / Rain command. Set required parameters in the "Rain Model" dialog:
 - Reference frequency = 23 GHz;
 - Reference polarization = H;
 - Reference attenuation (0.01%) = 15 dB
- Examine the Unavailability results. Note that the 0.01% attenuation (15 dB at the reference frequency 23 GHz, H-pol.) is about 30 dB at the operating frequency 38 GHz, same pol.
- Return to the Rain Intensity (Rec. 530-9) model (Customize / Propagation model command), then repeat the Rain Unavailability prediction process. Set Rain Intensity = 55 mm/h and display the Rain Unavailability diagram. Note that the 0.01% attenuation is again 30 dB.

This means that the "Frequency Scaling" model (as applied with the above data at 23 GHz) is equivalent to the "Rain Intensity" model with a 0.01% rain intensity = 55 mm/h.

End of HERALD Lab #6

HERALD Lab #7 – Interference Analysis

HERALD Functions

The following Herald functions are related to Interference Analysis :

- Prior to interference analysis, hop and equipment configuration must be suitably defined:
 - RF channels and polarization used in the active hop are defined in the Frequency Arrangement dialog (displayed by clicking the "Frequency Arrangement / Define" button in the "Hop Configuration" dialog).
 - Net Filter Discrimination (NFD) is defined in the "Interference - Net Filter Discrimination" dialog (displayed by the DataBase / Net Filter Discrim. command), where the interfering and interfered (victim) equipment and the relevant channel spacing are specified (interference analysis indicates if a potential interference cannot be evaluated because NFD is missing).
 - Antenna diagram is defined in the "Modify Antenna Data" dialog (displayed by the DataBase / Antenna command).
- The Evaluate / Interference commands start the interference search process. Depending on the selected command, the interference received / produced by the active hop or interference produced in the whole radio network is considered. The "Search Interference" dialog allows the operator to set the search limits (max distance, max frequency spacing, max S/I ratio).
- The Interference Report gives a list of interference exposures, including all the radio and topological data useful to characterize each interference.
- The Customize / Propagation models command displays the "Propagation Models" dialog, where the Interference correlation model can be specified.

Exercise 7.1 : Search interference



Note : In all the exercises in this Section Radio Site coordinates DO NOT represent realistic data if used to import path profiles. However path profiles are not needed here, site visibility is assumed in any case. If path profiles are imported from SRTM maps, they may exhibit anomalous behavior (totally obstructed paths or other unrealistic conditions).



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Interference1_Sample.hpf" (all the hops in this project operate at 15 GHz).

- In the "Radio Hops" dialog, select the ALPHA-ZEBRA hop and display the Hop Report. Check that the channel arrangement is already defined (last lines in the Configuration section of the Hop Report).
- Execute the File / Export Network to Google Earth command to get a view of network topology. Click NO in the box asking for saving a kml file. Radio sites and radio hops are displayed; keep open Google Earth, so that, going on with this exercise, you can compare interference search results with a network map. Click on the radio hop line to read hop length and frequency.
- Execute the Evaluate / Interference / From Any Hop to Active Hop command. In the "Search Interference" dialog set the search limits:
 - Max frequency spacing = 56 MHz;
 - Max distance = 200 km;
 - Max (faded) S/I = 100 dB.



Select the first visibility option (list on the right), so that line-of-sight conditions are assumed for all the interference sources.

- In the Interference Report (Useful Rx Site: ALPHA), check the various items in the list of interfering signals and in the interference sources table. Execute the Display / Interference / Toggle Site command to display the Interference Report, Useful Rx Site: ZEBRA ( Tip : Use the Herald Icon ).
- Similarly, test the other commands in the Evaluate / Interference menu. In particular, execute the From Any Hop to Any Hop command, do not modify the Search limits options, so that interference analysis is performed for all the radio hops in the present project.
- Select another hop as the Active Hop, then display the Interference Report using the Display / Interference / Received (or Produced) command.

Exercise 7.2 : Modify antennas



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Interference2_Sample.hpf". This is the same project used in the previous example, interference search parameters are already initialized.

- Select the ALPHA-ZEBRA hop and display the Interference Report (command Display / Interference Report / Received). Take note of the results, in particular, interference degradation = 4.3dB (print the report to make comparison easier).
- Go to the "Hop Configuration" dialog ( Tip : Use the Herald Icon ). Modify the antenna at the ALPHA site; select the antenna with code DDD1-15/60/S (second item in the list). Note that this antenna has the same diameter and gain of the previous one, but a large 3dB beamwidth and a lower directivity.
- Display the Interference Report again and compare the new results with the previous ones (in particular, interference degradation has increased to 7.4dB).
- Similarly, open again the Interference2_Sample.hpf" project and select the CHARLIE-DELTA hop. In the "Hop Configuration" dialog, modify the antenna at the DELTA site; select the antenna with code DDD1-15/60/S (second item in the list). Then, select the ALPHA-ZEBRA hop and display the Interference Report. Compare the results with the ones computed at the first step in this exercise (in particular, interference degradation has increased to 6.9dB).

Exercise 7.3 : Modify power levels



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Interference2_Sample.hpf". In the "Radio Hops" dialog, select the ALPHA-ZEBRA hop, as in the previous exercise. Take note of the interference results, in particular, interference degradation = 4.3dB (print the interference report to make comparison easier).

- Select the CHARLIE-DELTA hop and go to the "Hop Configuration" dialog. Clicking the "Losses/Degrad. / Define" button, insert in the DELTA site a TX attenuator = 10dB. Check the Hop Report and in particular the Rain Unavailability prediction (increased to about 10 minutes, because of the lower Tx Power = lower Fade Margin, but still acceptable).
- Return to the ALPHA-ZEBRA hop and display the Interference Report. Note that the interference degradation has decreased to 1.4dB).

Exercise 7.4 : Modify frequency/pol.



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Interference2_Sample.hpf". As in the previous exercise, select the ALPHA-ZEBRA hop and take note of the interference results. Display and print the Interference Reports, for both Received interference and Produced Interference (ALPHA and ZEBRA sites).

- Go to the "Hop Configuration" dialog. Click the "Freq. Arrangement / Define" button to display the Frequency Arrangement dialog. Modify the polarization setting, by clicking the "H<=>V Pol" button (below the table on the right).
- Display again all the Interference Reports (Received, Produced; ALPHA and ZEBRA sites) and compare them with the original ones (printed at the beginning of the present exercise). Note that a significant reduction in interference levels has been obtained with the new polarization in the ALPHA-ZEBRA hop.

Exercise 7.5 : Test rain correlation model



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Interference2_Sample.hpf". In the "Radio Hops" dialog, select the BETA-CHARLIE hop.

- Display the Interference Report and note that the interference to the BETA site, coming from the CHARLIE site (CHARLIE-DELTA hop) is labeled as "Correlated Interference" (both the useful and the interfering signals travel the same path and suffer the same rain attenuation).
- Select the ALPHA-ZEBRA hop and display the Interference Report. Note that the interference to the ALPHA site, coming from the DELTA site (CHARLIE-DELTA hop) is very high; the Rx angle, at the ALPHA site is about 2° only (see the Interference Sources table), so the interference path is very close to the useful path. However, this interference is NOT labeled as "Correlated Interference".
- Execute the Customize / Propagation models command to display the Propagation Models dialog. Note that Correlation Distance (lower frame on the left) is zero, so that Interference Correlation requires that Useful and Interference paths are identical. Modify Correlation Distance to 0.5 km, so that Correlation is declared also if Useful and interference paths are not identical, but very close.
- Display again the ALPHA-ZEBRA Interference Report. Note that the interference to the ALPHA site, coming from the DELTA site (CHARLIE-DELTA hop) is now labeled as "Correlated Interference". (Correlation Distance in the range 0.5-1.0 km appears as the most realistic design choice).

End of HERALD Lab#7

HERALD Lab #8 – ITU Objectives

HERALD Functions

The following Herald functions are related to ITU Performance Objectives :

- The basic parameters useful to define performance objectives are specified in the "Settings for ITU Objectives " dialog (Customize / ITU Objective parameters command). Such parameters are common to all the hops / sections in a given project.
- The "Section Data" dialog (Define / Sections) allows to define/modify Radio Section data. The user selects which are the applicable Recs and the link type relevant in that case (national / international; long-haul / short-haul / access; etc.). The SESR and Unavailability objectives are shown
- In the Section Report, the predicted Multipath Outage and Rain Unavailability results are shown for the selected Radio Section and should be compared with SESR and Unavailability objectives, respectively. The paragraph "Comparison with ITU-T / ITU-R Objectives " indicates which are the assumptions made to compute performance objectives.

Exercise 8.1 : Set basic parameters



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Object1_Sample.hpf". Close the "Radio Hops" dialog.

- Execute the Customize / ITU Objective parameters command to display the "Settings for ITU Objectives " dialog. Click the Default button, to be sure that all the parameters are initialized with default values.

- Modify some defaults as:


A1 (Block allowance to Long-haul sections) = 1%

C (Block allowance to Access sections) = 8.5%

Exercise 8.2 : International section



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Object2_Sample.hpf". Close the "Radio Hops" dialog. This is the same project as revised in the previous exercise.

- Execute the Define / Sections command; the "Radio Sections" dialog is displayed, click the Create button (the "New Section Data" dialog will be displayed)
- In the "New Section Data" dialog, select the ALPHA-BETA, BETA-CHARLIE, and CHARLIE-ECHO hops to define a new radio section, named "NorthSouth".
- In the "Section Data" dialog, check the "Set Performance Objectives" checkbox and select options to compute performance objectives, taking account that:
 - "NorthSouth" is a SDH radio section ( Tip: use G.828);
 - "NorthSouth" delivers international traffic to the terminating country;
 - It is estimated that 75% of total unavailability can be allocated to propagation events.
- Check the Unavailability and Error Rate objectives computed under the above assumptions.
- Close the "Section Data" dialog. In the "Radio Sections" dialog, click the Report button to display the Radio Section report. Comment on the displayed results.



Tip :



Compare predicted Multipath Outage with Error rate objectives and predicted Rain Unavailability with Unavailability (propagation) objectives.

Exercise 8.3 : Long-haul section



Run Herald; in the "Getting Started ..." Splash Screen click the Open Project icon to open the "Object2_Sample.hpf". Close the "Radio Hops" dialog.

- As in the previous exercise, define a Radio Section, named "MultiRegion", with hops ALPHA-BETA and BETA-CHARLIE.

- In the "Section Data" dialog, check the "Set Performance Objectives" checkbox and select options to compute performance objectives, taking account that:
 - It is required to test performance objectives at the channel level (below primary rate) ( Tip: use G.821);
 - "MultiRegion" deliver traffic from an International Gateway to a Primary Center ( Tip: High grade link);
 - It is estimated that 50% of total unavailability can be allocated to propagation events.


- As in the previous exercise, check computed objectives in the "Section Data" dialog. Then display the Section Report and take note of the displayed results.

Exercise 8.4 : Access section



As in the previous exercise, run Herald and open the "Object2_Sample.hpf" project.

- Define a Radio Section, named "Local", with only one hop (BETA-DELTA).

- In the "Section Data" dialog, check the "Set Performance Objectives" checkbox and select options to compute performance objectives, taking account that:
 - "Local" is a SDH radio section ( Tip: use G.828);
 - "Local" is in the National / Access portion of the network;
 - It is estimated that 50% of total unavailability can be allocated to propagation events.

- As in the previous exercise, check computed objectives in the "Section Data" dialog. Then display the Section Report and take note of the displayed results.

Exercise 8.5 : North America Standard Objectives



As in the previous exercise, run Herald and open the "Object2_Sample.hpf" project.

- Close the “Radio Hops” dialog and execute the toggle command Customize / ITU-North America Objectives in order to activate North America standard.
- Execute the Define / Sections command to define a Radio Section named "ShortHaul", with hops ALPHA-BETA and BETA-CHARLIE.
- In the "Section Data" dialog, check the "Set North America Std Objectives" checkbox and select the BellCore Short-Haul option (1600 sec/year, 250 miles, One-way, equivalent to 99.995% reliability).
- Close (OK) the "Section Data" dialog and click the Report button in the "Radio Section" dialog to display the Radio Section report. Comment on the displayed results. BellCore objective for Total Annual Propagation Reliability is not satisfied.
- Again, execute the Define / Sections command; in the "Radio Section " dialog, click the Modify button; in the "Section Data" dialog set a less stringent Customized objective, similar to BellCore objective (99.995% reliability, 250 miles), but adding a "Flat Reliability Objective" up to a 50 mile Minimum Distance.
- Display Section Report with the new objective. Comment on the displayed results.



Tip :

The Flat Reliability Objective up to a Minimum distance means that accepted outage time is not reduced to extremely low values for very short radio sections. See Herald Help (press F1 key to display the help page "Section Data dialog box, North America Standard") where different objectives options are discussed.

End of HERALD Lab#8

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