Regular paper

Reliability of line-of-sight radio-relay systems

Jan Bogucki and Ewa Wielowieyska

Abstract— The modern radio transmission systems are specifically designed for catching principally two main objectives: on one side to provide a radio solution for long distance where large configurations are required to fulfill the high capacity transmissions needs, on the other side to guarantee link quality as high as possible. The availability of a radio-relay system is dependent upon many factors and particularly upon: the reliability of equipment and propagation conditions. The article describes the wave propagation and equipment that determine the performance of a radio-relay path. National Institute of Telecommunications (NIT) carried out research on propagation phenomena on terrestrial path and exemplary results are described herewith. The availability of radio equipment based on the mean time between failures for equipment modules is presented too.

Keywords— line-of-sight radio links, propagation, equipment, reliability.

1. Introduction

Time operation of radio links is split into two periods, when it is in working order or out of order. Radio links are out of order when even one of its basic parameters is crossing permissible limit spread. This occurrence is called failure. It is not essential the failure to follow rapidly or gradually. The total unavailability of radio path is the sum of the probability of hardware failure and unavailability due to propagation conditions.

There are six transmission parameters, which may be used to characterize of unsatisfactory quality performance. These are bit error ratio (BER) or frame error rate (FER), short interruption, delay, jitter, slip and quantizing noise. The ratio BER/FER and short interruption are the main indicators of unavailability. This is because jitter and slip will cause bit errors and short interruption in the network and that delay and quantizing noise are relatively fixed quantities in any connection.

Line-of-sight radio-relay systems are defined unavailable when one or both of the following conditions occur for more than 10 consecutive seconds:

– the digital signal is interrupted,

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

It should be noted that the unavailability for system has to be considered for both "the go" and "the return" direction, that is twice the calculated value.

2. Link availability (reliability)

Many fixed broadband wireless links are designed to be available essentially at all times. Available A means that BER or FER is at or below a given quality threshold level:

$$A\ [\%] = \frac{100\ (total\ usage\ time - downtime)}{total\ usage\ time}\,.$$

Conversely, an outage is the time when the link is not available. An outage of only 53 mines a year is an availability of 99.99%. The availability percentage is usually based on an annual average although link outage due to fades is normally calculated on a worst month basis.

The annual outage time is simply related to percentage availability by:

$$outage\ time = \left(1.0 - \frac{percent\ availability}{100}\right) 525600\ \text{min}\,.$$

An outage can occur for a variety of reasons, including multipath fades, rain fades, diffraction fades and equipment failures. Calculating the probability that fades of a particular magnitude occur, or equipment failures occur, will lead directly to the probability of an outage and hence the link availability probability.

3. Causes of unavailability

The availability of a radio-relay system is dependent upon many factors and particularly upon: the maintenance organization (which determines the time to restore), the reliability of equipment's and the system design and propagation conditions. The relative importance of these various factors may vary significantly, sometimes without possibility of control, from one area to another.

System planners should take into account all causes of interruption or quality degradation affecting system unavailability. Features of the major causes of unavailability in radio-relay systems are described below.

Equipment. Estimate of unavailability should include all causes which are statistically predictable, unintentional and resulting from the radio equipment. Such causes can be as follows:

– failure or degradation of radio equipment including modulators and demodulators,
– failure of auxiliary equipment such as switch-over equipment,
– failure of radio system power supply equipment,
– failure of antenna or feeder.

Propagation. System interruptions due to deep multipath fading often recover within 10 s, however, they sometimes occur for more than 10 s causing unavailability. Excessive precipitation-attenuation due to heavy rainfall or snow fall lasts for a fairly long time and causes unavailability in systems operating in the frequency bands above 10 GHz. Fading due to layering of the atmosphere is the dominating factor of degradation of radio-relays in the frequency bands below 8 GHz. It may be possible to derive prediction statistics on propagation effects by applying the formulae or methods given in [4] and [5]. Also, since there is generally a low probability of heavy precipitation occurring, the unavailability time it causes may differ from year to year.

Diffraction fades. When there are two radio antennas located on or near the Earth's surface propagation can ordinarily occur between them by groundwave. If an obstruction, a hill, a mountain, a building intervenes, propagation can still occur via slant paths over the top edge of the obstruction. This depends on diffraction over the edge. There is an additional loss due to diffraction. For zero diffraction loss the direct line of sight path between transmitter and receiver must clear the obstruction by several wavelengths. When the direct path just grazes the obstruction diffraction loss is exactly 6 dB.

Other causes. Unpredictable noise bursts due to interference mainly from sources outside the interfered with system may cause unavailability when the noise power exceeds a certain threshold. This kind of interruption includes interference from space systems or radar systems associated with anomalous propagation. Human intervention during maintenance activities can also cause unavailability.

4. Propagation affects error performance and availability objectives

Fading due to condition of the atmosphere is the dominating factor of degradation of radio-relays. Fading (being random variable) can cross threshold only in specific period of time. Fading events are mainly caused by multipath in range of frequency below 8 GHz and by precipitation in range above 20 GHz. Definition probability of appearance those events are great of importance on reliability of line-of-sight radio-relay systems.

Transmission of microwave signals above 10 GHz is vulnerable to precipitation. The attenuation due to absorption is larger than attenuation due to scatter for wavelengths that are until compared with the drop size. For wavelengths that are short compared to drop size, the attenuation due to scatter is larger than due to absorption.

Multipath fadings are especially dangerous in high capacity systems, where signal spectrum occupied comparative frequency wide band. Formulas mathematical describing these phenomena are given in [4] and [5]. Meteorological conditions in the space separating the transmitter and the receiver may sometimes cause detrimental effects to the received signal. Rays that normally would have been lost in troposphere may be refracted into the receiving antenna where they are added to the wanted signal. The phase- and amplitude-relationship between signals determines the resultant input signal at the receiver. Multipath fadings triggering off deep notch in transfer function of radio links cause the increasing BER because of that:

- decreasing signal to noise ratio,
- decreasing signal to interference ratio,
- decreasing separation between two orthogonal components I and Q.

The prevision of attenuation which may arise in the radio link channels are due to multipath and atmospheric precipitation demanding knowledge of either the probability distribution of precipitation intensity or of the probability distribution condition propagation along the determined routes. Taking into consideration the nature and the necessity of research on propagation effects occurring in radio links, detailed instructions and requirements, which should be met to prepare self-operating measuring position, have been described in [2, 5]. Furthermore such position has been produced and set-up to work with radio links receivers. The radio links have been developed to test propagation in band X, Ka and Q. This paper describes the example tests results of wave attenuation in above mentioned radio links.

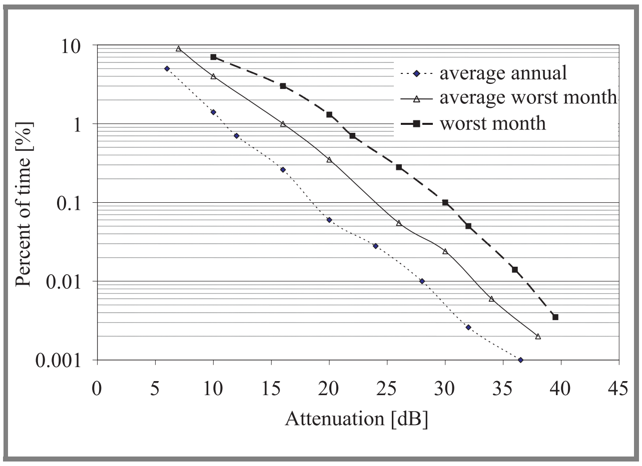

Fig. 1. The average worst month and the worst month attenuation distributions in 5-year period in comparison with the average annual distribution for 6 GHz and 52.3 km route.

For example, Fig. 1 shows the average worst month and the worst month attenuation distributions in 5 year-period in comparison with the average annual distribution for 52.3 km route. At the National Institute of Telecommunication (NIT) it has been researched into precipitation fading on line-of-sight radio links too.

For example, Fig. 2 shows 18.6 GHz frequency and 15.4 km route in 2-year period.

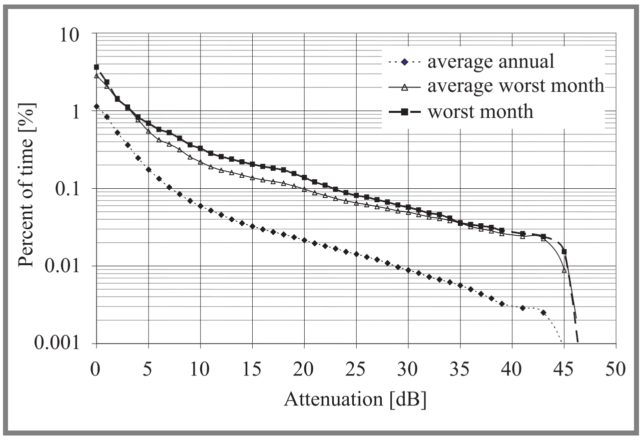

Fig. 2. The average worst month and the worst month attenuation distributions in 2-year period in comparison with the average annual distribution for 18.6 GHz and 15.4 km route.

Atmospheric disturbances affect the transmission conditions for the line-of-sight radio-relay systems. The received signal will vary with time and the system performance is determined by the probability for the signal level drop below the radio threshold level or the received spectrum to be severely distorted. Hence it is important to choose optimal frequency for working radio link, its diameters of parabolic antennas, transmitter power and receiver characteristic. In order to estimate the performance of a radio link system, a link power budget has to be prepared. The difference between nominal input level and radio threshold level, the fading margin are the main input parameters in the performance prediction model.

Table 1

Power budget of radio links 6 GHz and 18 GHz

Parameters	6 GHz, 50 km	18 GHz, 15 km
Transmitter output power [dBm]	+20	+20
Feeder loss transmitter [dB]	1	1.2
Branching loss [dB]	1.5	1.6
Transmitter antenna gain [dB]	39	45.2
Free space loss [dB]	142	141
Receiver antenna gain [dB]	39	45.2
Feeder loss receiver [dB]	1	1.4
Nominal input level [dB]	–43.5	–36.4
Receiver threshold [dB]	–71	–70
Fading margin [dB]	–27.5	–33.6

Nominal input level means power on input receiver for normal propagation condition, i.e., without attenuation due to multipath or precipitation.
Lets consider typical radio link capacity STM-1 (Table 1):

- 6 GHz frequency, 50 km path length, 1.8 m diameters of parabolic antennas;
- 18 GHz frequency, 15 km path length, 1.2 m diameters of parabolic antennas.

The link budget for the radio links of 50 km path and 6 GHz frequency is shown on Fig. 3. In comparison the results

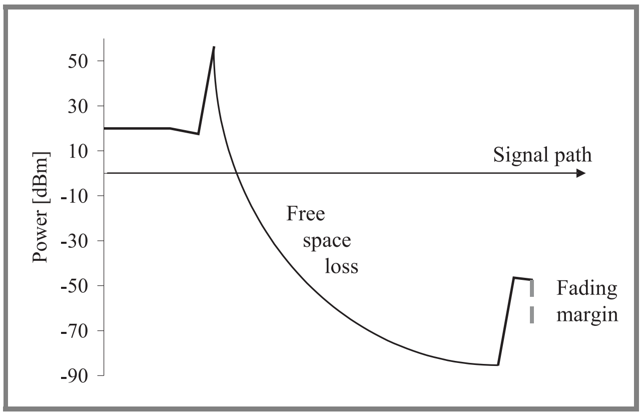

Fig. 3. Transmit/receive system and its link budget.

power budget with data on Fig. 1 it can be affirmed this fading margin assures 0.21% in the worst month, i.e., 0.42% duplex transmission. In comparison the results power budget with data on Fig. 2 it can be affirmed this fading margin assures 0.04% in the worst month, i.e., 0.08% duplex transmission.

5. Equipment failure rate

The probability that electronic equipment fail is not constant with time. Initial and wear-out failures give higher probability during the burn-in and wear-out periods. We concentrate on the useful lifetime where random failures give a constant probability.
After the burn-in period, the equipment failure rate is assumed to be constant until the wear-out period starts, and the equipment reliability can be predicted using analytical methods. If the failure rate is λ, the probability of m failures when testing n equipment modules in a unit time is given by the binomial distribution:

$$p_m = \frac{n!}{m!(n-m)!}\lambda^m(1-\lambda)^{n-m}. \tag{1}$$

The mean value of this distribution is given by

$$\sum_{m=0}^{n} p_m m = n\lambda. \tag{2}$$

The average number of surviving equipment modules after unit time is given by

$$N_{av} = n - n\lambda \,. \tag{3}$$

The number of surviving equipment modules vary with time t on average and is given by

$$n = n_0 e^{-\lambda t}\,, \tag{4}$$

where n_0 is initial number of equipment modules.

A constant failure rate gives an exponential decrease of surviving equipment modules.

Mean time between failures. If the failure rate per unit time equals λ, the mean time between failures (MTBF) T_{av} is Δt:

$$\Delta t = \frac{1}{\lambda}\,. \tag{5}$$

Calculation of unavailability. Mean time between failures $T_{av} = \Delta t$ is more convenient to use than λ when calculating unavailability. The unavailability of one equipment module (Fig. 4a) is given by

$$N_1 = \frac{T_{n_0}}{T_{av} + T_{n_0}}\,, \tag{6}$$

where T_{n_0} is mean time to repair (MTTR).

For telecommunication equipment:

$$T_{av} \gg T_{n_0} \tag{7}$$

and Eq. (6) may be approximated by

$$N_1 = \frac{T_{n_0}}{T_{av}}\,. \tag{8}$$

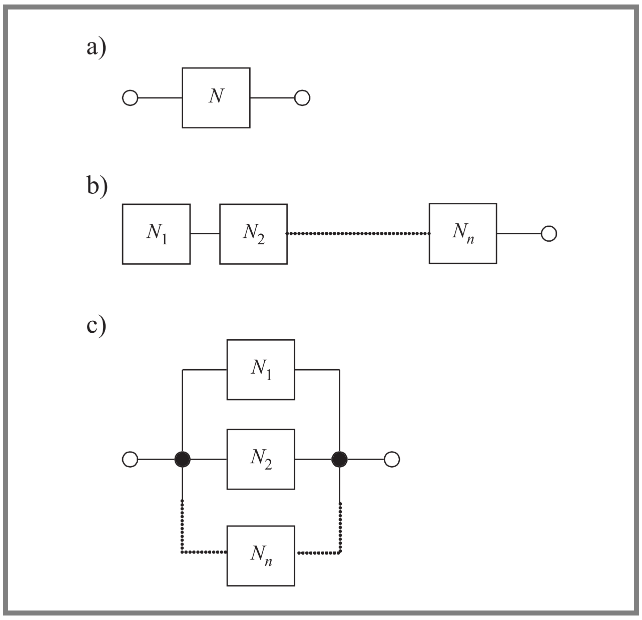

Fig. 4. One equipment module (a), cascaded modules (b) and parallel modules (c).

Unavailability of cascaded modules. The system in Fig. 4b will be available only if all the modules are available simultaneously. The availability of the total system is given by

$$A_s = \prod_{j=1}^{n} A_i = \prod_{i=1}^{n} (1 - N_i)\,. \tag{9}$$

The corresponding unavailability is given by

$$N_s = 1 - A_s = 1 - \prod_{i=1}^{n}(1 - N_i) \approx 1 - \left[1 - \sum_{i=1}^{n} N_i\right] = \sum_{i=1}^{n} N_i\,. \tag{10}$$

So, when the unavailability is much smaller than availability, the unavailability of a system of cascaded modules is the sum of the unavailability's of its individual modules.

Unavailability's of its individual modules. Modules may be connected in parallel. The system will then unavailable only if the modules are unavailable simultaneously. The unavailability is given by

$$N_s = \prod_{i=1}^{n} N_i\,. \tag{11}$$

Protection switching. Continuous monitoring of digital radio-relay system is necessary for initiating protection switching under conditions of channel failure. Protection switching is often effective to improve system availability. In radio-relay systems the so-called multi-line switching method is usually used. In this method one or r ($r > 1$) protection radio channels are prepared for k working channels. When one of the k working channels is interrupted the signal in the interrupted channel will immediately be recovered by one of the protection channels over s radio hops. In such a case, the unavailability N of each both-way radio channels due only to equipment failure, assuming that the failure rate of switching equipment is negligibly small, can be expressed by the following formula:

$$N = \frac{2}{k}\left[\binom{k+r}{r+1}\right](sU)^{r+1}\,, \tag{12}$$

where s is number of radio hops contained in a switching section and U is probability of an interruption of each hop (as far as equipment failure is concerned, U = MTTR/MTBF):

$$\binom{k+r}{r+1} = \frac{(k+r)!}{(r+1)!(k-1)!}\,. \tag{13}$$

In many cases the number of the protection channels $r = 1$ and formula (12) can be written by the following:

$$N = \frac{2}{k}\left[\binom{k+1}{2}\right](sU)^2\,. \tag{14}$$

Protection switching is effective not only for equipment failure but also for multipath fading through frequency diversity.

Equipment failures of modern radio links. The latest radio-relay systems are designed to be highly reliable and the MTBF becomes extremely long. For high reliability link systems that must have outages of only a few minutes a year, equipment failure can play an important part in achieving this reliability. Equipment failure can come from component failure in the equipment itself or physical damage to the equipment from violent weather or vandalism. If a microwave relay site is on a remote mountaintop, access by road or even by helicopter to repair a problem can take several hours or longer. A single such failure alone may violate the reliability objective of the system. The equipment reliability is usually given as MTBF. This is a published equipment specification that varies from 50 000 h (5.7 years) to about 300 000 h (34.2 years) for currently available microwave link equipment. The mean time to repair must also be considered in looking at the overall probability of an probability that a single link terminal will fail is

$$terminal\ outage\ probability = 1.0 - \left(\frac{\mathrm{MTBF}}{\mathrm{MTBF}+\mathrm{MTTR}}\right) \tag{15}$$

or 0.00790% for the sample values.

The link fails when the terminal at either end fails, so the link failure probability due to equipment failure is 0.0159% or a link availability of 99.984%. For a link with a high fade margin, the equipment outage probability can dominate the overall link availability.

A link that has a single terminal radio is often referred to as unprotected because of equipment failure may not be acceptable when considering the availability requirements. For this reason, systems intended for high reliability applications usually employ redundant equipment at each terminal. Redundant radio equipment is usually referred to as hot standby equipment, indicating that the equipment is turned on and at operating temperature. It may then be immediately and automatically put into service in the event of failure radio units. A rapid switching process between primary and secondary units interrupts the signal for 20 to 50 ms.

With a hot standby terminal, for the example with the numbers used above, the link availability is 99.99999984%. This availability is substantially higher than can be expected from multipath and rain fade outages, removing equipment failure as a significant factor in determining overall link availability.

Human intervention during maintenance activities can also cause unavailability. The contribution of these factors is generally difficult to predict through mathematical analysis. However, they should be considered when designing radio-relay systems.

At the National Institute of Telecommunications "TrasaZ" computer program has been worked out. This is a radio frequency propagation computer program for the transmission path between an RF transmitter and a receiver. This program compute fades expected from multipath and rain. Earth curvature for standard or substandard atmosphere is taken into account. The program's frequency range is from 1 GHz to 60 GHz.

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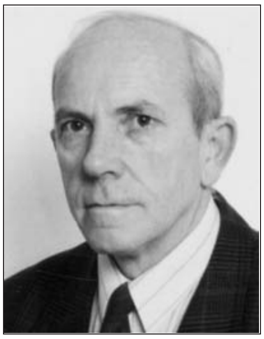

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