

RECOMMENDATION ITU-R F.1101

**CHARACTERISTICS OF DIGITAL RADIO-RELAY SYSTEMS
BELOW ABOUT 17 GHz**

(Question ITU-R 135/9)

(1994)

The ITU Radiocommunication Assembly,

considering

- a) that it is preferable to define certain aspects of the characteristics of digital radio-relay systems (DRRSs) operating below about 17 GHz in order to facilitate system design;
- b) that digital radio-relay system characteristics are determined by the gross bit rate, modulation method, spectrum shaping, interference susceptibility and other relevant factors;
- c) that adaptive techniques offer effective countermeasures to adverse propagation conditions and a means of reducing interference in certain circumstances. These techniques are particularly suitable for large bandwidth systems and for systems using complex modulation schemes;
- d) that multi-state modulation is an effective method for increasing spectrum utilization efficiency;
- e) that when spectrum efficiency is not a major issue, more simple modulation schemes (up to four states) are also suitable for low and medium capacity systems,

recommends

1. that the factors contained in Annex 1 should be taken into consideration in the design of digital radio-relay systems operating below about 17 GHz.

Note 1 – The material contained in this Recommendation is for guidance only. DRRS are not required to have all the features listed herein but can make use of one or several of them, depending on the application for which they are designed.

ANNEX 1

Factors to be considered in the design of digital systems operating below 17 GHz**1. Categorization of digital radio-relay systems**

It seems advisable to subdivide digital radio-relay systems into the following categories:

- low capacity radio-relay systems for the transmission of digital signals with gross bit rates up to and including 10 Mbit/s;
- medium capacity radio-relay systems for the transmission of digital signals with gross bit rates ranging from 10 Mbit/s up to about 100 Mbit/s;
- high capacity radio-relay systems for the transmission of digital signals with gross bit rates greater than 100 Mbit/s.

2. **Predominant propagation factor**

Error performance and availability are representative parameters featuring digital radio-relay systems. As far as the propagation path characteristics are concerned, rain attenuation predominates at frequencies above about 17 GHz, while multipath distortion predominates at frequencies below about 10 GHz.

For this reason, digital radio-relay systems should be mainly designed in terms of unavailability at frequencies above 17 GHz and error performance at frequencies below about 10 GHz, while in the range 10-17 GHz both objectives should be considered.

3. **Modulation and coding techniques**

Coding and modulation techniques used are of particular concern to the radio-relay system. Coding consists of a transformation of the format of the signals in the alphabet to take account of the methods of synchronization, introduction of redundancy in accordance with the error-control and/or correction system (forward error correction), spectrum shaping and to meet the requirements of interfacing with the transmission medium or channel. Modulation consists of transferring information in the baseband signal onto an RF carrier. In general, this is achieved by a single change or combined changes in the phase, frequency or amplitude of the RF carrier for radio-frequency transmission.

3.1 ***Comparison of some methods of modulation***

Different modulation techniques may be compared theoretically on the basis of their Nyquist bandwidth and the normalized carrier-to-noise ratio. The real carrier-to-noise ratio (allowing for all imperfections) needs to be considered in order to define real systems.

Detailed information on this subject is given in Appendix 1.

3.2 ***Modulation methods***

A suitable modulation method is selected by taking into account the system requirements. For instance, if spectrum efficiency is not a major issue and/or high interference tolerance is important, a simple modulation method should be used. The features of simple modulation methods are:

- easy implementation in all frequency bands,
- robustness against propagation effects,
- high tolerance against all kinds of interferences,
- high system gain characteristics.

On the other hand, a multi-state modulation method improves spectral efficiency on a route. Typical applications for multi-state modulation methods are high capacity trunk, junction and access networks.

Careful design of the multi-state constellation for QAM schemes might achieve some system gain against non-linear distortion while retaining a fairly simple implementation.

Consideration of the carrier-to-noise requirement for the same BER when changing from 16-state to 512-state modulation, for example, shows the need for significant increases in peak power, average power and peak-to-average power ratio. This places more stringent requirements on the high power amplifier, and will in many cases require the use of linearization measures, such as pre-distortion.

3.3 ***Data coding and error correction***

In order to improve the tolerance of the modem to various sources of C/N impairment, data coding and error correction techniques may be used for radio systems employing multi-state modulation schemes.

The introduction of forward error correction coding is also useful for reducing the residual bit errors. Various types of codes are employed in multi-state modulation schemes. It should be noted that code efficiency is required for band-limited digital radio applications.

3.3.1 Forward error correction

There are several types of error correction techniques. One involves the use of error correction codes such as block codes and convolutional codes, where redundant parity bits are inserted into the time domain.

In the conventional method of forward error correction, the incoming data are passed through an encoder which adds redundant parity bits. The combined set of information and parity bits are then modulated and transmitted. Upon reception, the demodulated data are subjected to a symbol-by-symbol hard decision on each demodulated symbol. The demodulated symbols are then decoded to extract the information bits with appropriate corrections as governed by parity bits.

3.3.2 Coded modulation

This method is a technique that combines coding and modulation which would have been done independently in the conventional method. Redundant bits are inserted in multi-state numbers of transmitted signal constellations (see Appendix 1). This is known as coded modulation. Representative examples of coded modulation are block coded modulation (BCM), trellis coded modulation (TCM) and multi-level coded modulation (MLC or MLCM). In BCM, levels are coded by block codes whereas TCM uses only convolutional codes. On the other hand, different codes can be used for each coded level in MLCM, so MLCM can be seen as a general concept that includes BCM and to some extent TCM. These schemes require added receiver complexity in the form of a maximum likelihood decoder with soft decision. Tables 1a and 1b provide indications of expected performances.

A technique similar to TCM is the partial response, sometimes called a duo-binary or correlative signalling system. A controlled amount of intersymbol interference, or redundancy is introduced into the channel. Hence, the signal constellation is expanded without increasing the transmitted data bandwidth. There are various methods utilizing this redundancy to detect and then correct errors to improve performance. This process is called ambiguity zone detection or AZD.

Additional information on BCM, TCM, MLCM and partial response with AZD is given in Appendix 2.

4. Radio spectrum utilization efficiency

Radio spectrum utilization efficiency is an important factor to be considered in the design of digital radio-relay systems and it is determined by the “information transferred over a distance” in relation to the frequency bandwidth utilization, the geometric (geographic) spatial utilization and the time denied to other potential users. The measure of utilization (U) is given by the product:

$$U = B_{RF} \cdot S \cdot T$$

where:

B_{RF} : radio-frequency bandwidth occupied

S : geometric space occupied (usually area for radio-relay systems)

T : time.

The utilization efficiency E for a system operating continuously in time is expressed by:

$$E = \frac{2 \cdot N \cdot B}{B_{RF} \cdot S}$$

where:

N : total number of “go” and “return” channels in the radio band B_{RF}

B : channel gross bit rate.

In the case of single high or medium capacity multi-channel long-haul routes, in which spurious emissions are adequately controlled and the dimensions of space and time can be ignored, the radio-frequency spectrum utilization efficiency reduces to a bandwidth utilization efficiency E_B , given by:

$$E_B = \frac{2 \cdot N \cdot B}{B_{RF}}$$

where N includes both polarizations on the route.

It can be seen that the use of multi-state modulation methods increases the bandwidth utilization efficiency in this case by an increase of B .

Detailed information on this subject is given in Recommendation ITU-R SM.1046.

5. Technical basis of co-channel and alternated arrangements for digital radio-relay systems

5.1 Parameters affecting co-channel and alternated radio-frequency arrangement

This subject is described in *recommends* 2 of Recommendation ITU-R F.746.

5.2 Shaping filter requirements

Channel shaping filtering may, in principle, be performed at baseband, intermediate or radio frequencies. It must be designed so as to control the overlap of adjacent spectra.

Generally, transmitter and receiver filters, used to control adjacent frequency channel interference and to restrict the receiver noise bandwidth, are designed to have a Nyquist raised cosine roll-off shaping, which theoretically does not give intersymbol interference.

The roll-off factor, α , of such a Nyquist filter may be chosen taking into account that, for a theoretical no-interference condition, the following relation applies:

$$\alpha \leq x - 1$$

where x is the width of the radio-frequency channel normalized with respect to the symbol frequency.

The balance between allowable interference level for the chosen modulation format, the increase of peak-to-average carrier power requirements (as reported in Appendix 1) and the reduction of the timing margin for a no intersymbol interference condition, governs practical implementations.

6. Technical bases of performance and availability objectives for digital radio-relay systems employing multi-state modulation

In order to efficiently utilize the limited resource of radio-frequency spectrum, multi-state modulation schemes may be employed for high capacity digital radio-relay systems. As the number of modulation states increases, the performance of the modem and the radio system is impaired by several factors. These are:

- the stability of carrier and clock synchronization circuits,
- amplitude distortion due to the transmission path,
- distortion caused by saturation of the high power amplifier,
- interference from other systems (adjacent channels, satellite, adjacent route, etc.),
- multipath fading.

It is therefore necessary to consider the mechanisms causing the impairments and devise the appropriate countermeasures. The following topics should be studied. Fuller details may be found in Recommendation ITU-R F.1093.

6.1 Factors affecting error performance

Waveform distortion and interference during multipath fading are dominant factors in determining the severely errored seconds in digital radio-relay systems operating below about 10 GHz. Both factors have to be taken into account when designing digital radio systems.

The following gives a brief introduction to many methods used to estimate the effects of propagation on the performance of digital radio.

6.2 Susceptibility to multipath fading

6.2.1 System signature

Digital radio-relay systems are particularly affected by the frequency selective nature of multipath fading. Fading effects on a radio may be characterized by a “system signature”. Numerical methods with computer simulation could be useful for signature computation. A “system signature” is basically a static measure of the susceptibility of a particular equipment to a two ray model of the multipath channel in both minimum phase and non-minimum phase conditions. It is being used as a basis for equipment comparisons.

An important aspect of multipath fading is its dynamic nature. Therefore dynamic tests should be performed to assure satisfactory equipment performance. Dynamic multipath fading may be simulated in the laboratory by a dynamic simulator capable of simulating the time sequences of multipath fading. These tests will allow the optimization of synchronization and equalizer coefficient adaptation circuits.

Further studies are needed to define optimum test sequences for dynamic testing.

6.2.2 Normalized signature

Another approach to the use of waveform factor is the use of a normalized signature constant. This constant can be derived from theoretical signature and/or measurements and can be used to compare modulation methods and countermeasures such as equalizers and diversity.

6.3 Countermeasures to multipath fading

In order to mitigate the propagation impairments, various countermeasures such as space diversity, frequency diversity, angle diversity and adaptive equalizers in the time and frequency domains are described in Recommendation ITU-R F.752.

6.3.1 Equalizers

Technological advances in equalization techniques have been very effective in minimizing the effects of anomalous propagation on digital radio performance. As the number of modulation states increases, the radio system becomes more vulnerable to multipath fading. Various types of adaptive equalizers are currently in use for digital radio-relay systems and are implemented at intermediate and/or at baseband frequencies. Among these equalizers, decision-feedback equalizers and linear transversal equalizers are in common use. A powerful solution is represented by the so-called fractionally-spaced linear transversal equalizer (FSLTE), in which the signal is sampled several (at least two) times within one symbol period. Such a solution shows a better performance/complexity ratio, together with a lower sensitivity to timing phase (when the central tap is not fixed). Moreover, FSLTEs, implemented with a two samples/symbol sampling, combine “naturally” with receiver over-sampling digital filtering (shaping filters), and with simplified minimum mean square error (MMSE) algorithms for timing recovery.

For optimum performance, the dynamic convergence of FSLTEs should be accomplished by means of “blind” algorithms (as with synchronous LTE), combined with the recursive updating of tap coefficients, reference-tap position and timing phase, for both initial convergence and channel tracking.

6.3.2 Multi-carrier transmission

A multi-carrier transmission method in which the symbol rate can be decreased in proportion to the number of carriers of the multi-carrier system is also an effective technique to mitigate induced waveform distortion. The waveform factor may be used to assess the relationship between symbol rate and modulation method for a particular outage budget. This relationship is given in a pictorial form in Recommendation ITU-R F.1093, from which the maximum symbol rate that may be transmitted for a given modulation scheme may be established, once an outage budget is specified.

If the gross data rate to be transmitted exceeds the corresponding value calculated from the symbol rate in the above method, then the use of multi-carrier techniques may be necessary. It is also possible to determine the number of carriers needed in the multi-carrier case.

In general, the use of a multi-carrier method requires the development of higher linearity power amplifiers and the optimization of sub-carrier spacing to avoid intermodulation distortions and intra-system interference produced by adjacent carriers of the same multi-carrier system.

6.4 Susceptibility to interference and noise

Consideration of various kinds of interferers arising in a radio system is important in the choice of a modulation scheme and the associated hardware needed.

Adjacent cross-polarized channel interference (ACI) may become one of the main factors in the design of radio systems. The value of ACI is dependent upon antenna cross-polar discrimination (XPD). As the XPD degrades during fading, ACI may become crucial in noise budget calculations of the radio system. In order to minimize the detrimental effects of ACI on 64-QAM and other multi-state modulation methods, improved antenna XPD or a smaller roll-off factor pulse shaping filter may be necessary.

The factor, W , also gives a measure of the received carrier power level required to maintain a given level of degradation from fixed broadband interference, as the symbol rate is varied. However, when interference is between a number of similar transmissions, all with symbol rates, occupied bandwidth and relative spectral positions reduced in the same ratio, the degrading effects can only be maintained at a constant level by introducing some means of compensatory interference reduction – for example, improved antenna discrimination (at network nodes), improved XPD, or larger RF channel spacings (on a route). If this last expedient is adopted, improvement in spectrum utilization efficiency on a route is no longer inversely proportional to symbol rate. The magnitude of the interference reduction required is proportional to the change in the value of W and to the ratio of symbol rates.

Various interference factors introducing ground scattering become more significant in multi-state modulation systems (see Recommendation ITU-R PN.530).

The outage probability due to thermal noise and interference is given by (see Recommendation ITU-R PN.530):

$$\begin{aligned} P_n &= a_m \times 10^{-A/10} && \text{single antenna reception} \\ &= (a_{SD} / (1 - \rho_s)) \times 10^{-A/5} && \text{space diversity reception} \end{aligned}$$

where:

- A : system flat fade margin (dB)
- a_m, a_{SD} : constants determined by frequency, path length and path parameters
- ρ_s : spatial coefficient between two antennas.

Suppose that the outage probabilities due to waveform distortion and interference noise are represented as P_d and P_n , respectively. The total outage probability (P_0) may be evaluated from the composite fade margin concept, for example:

$$\begin{aligned} P_0 &= P_d + P_n && \text{single antenna reception} \\ &= (\sqrt{P_d} + \sqrt{P_n})^2 && \text{space diversity reception} \end{aligned}$$