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Basic Circuit Reliability for digital HF Ionospheric Communications

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ABSTRACT

Modern radio communication systems require estimates of basic circuit reliability to assess the probability that satisfactory performance will be achieved. For these, a knowledge is needed of both propagation effects and operational requirements. An internationally adopted calculation method exists for HF analogue systems based on satisfying defined signal/noise ratios, but for digital systems attention must additionally be paid to meeting maximum permitted dispersion criteria. A new method of evaluation to achieve this is introduced as an extension of the procedure for analogue systems. The various inherent assumptions are discussed and the justification for the adopted approach is examined.

Key words: B+M Ionosphere, HF Radio-wave propagation, Digital system performance.

1. INTRODUCTION

Traditionally, the planning of HF radio systems has involved the estimation from propagation considerations for different times of day of the band of frequencies between the monthly median values of basic MUF (the highest frequency supporting ionospheric propagation by refraction) and the LUF (lowest frequency with adequate signal strength). Estimates of median signal strengths derived by taking account of the various transmission loss and gain factors have been combined with background intensity estimates for atmospheric, man-made and galactic noise to give median signal/noise ratios.

Whilst in some circles the use of empirical fading allowance adjustments to such monthly figures remain favoured, a more precise approach should take account statistically of the day-to-day and within-an-hour variations of the signals and noise. This is done through the concept of reliability

(ITU-R, 1997a), and various types of reliability are defined. Reliability is the probability of achieving a desired system performance. Basic reliability applies when the background is the composite of atmospheric, man-made and galactic noise; overall reliability also allows for interference. Basic circuit reliability (BCR) relates to a single point-to-point circuit. Basic reception reliability considers the multiple transmission of the same information at different frequencies, and basic service reliability applies as in broadcasting where reception is to a number of separate points within a required area. These different types of reliability each may be evaluated in terms of the BCR (ITU-R, 1997a).

2. BCR FOR AN ANALOGUE CIRCUIT

For a radio system with performance determined only by signal/noise considerations we have that:

$$\mathrm{BCR} = \int_{\mathrm{SN}_0} \mathrm{P(SN)} \cdot d(\mathrm{SN}) \qquad (1)$$

where P(SN) is the probability-density function of the combined day-to-day and within-an-hour variations of SN and SN_0 is the required signal/noise ratio. A method of evaluation of eq. (1) is given in ITU-R (1997a) using reference values of the upper and lower decile deviations from the monthly median of the signals and of the noise. It is assumed that the signals and noise are uncorrelated, and that the upper decile signal/noise ratio deviation from the median is given as the rms sum of the upper decile deviations of the signals due to day-to-day and within-an-hour variations, and the lower decile deviations of the composite noise as appropriate due to day-to-day and within-an-hour variations, where all quantities are expressed in decibel form. Likewise, the lower decile signal/noise ratio is given in terms of the corresponding lower decile signal and upper decile noise deviations. A simple approximate, but adequate, form of cumulative-probability distribution produced by Bradley and Bedford (1976) given entirely in terms of the median, upper and lower decile deviations of signal/noise ratio (Fig. 1) is incorporated to yield BCR for any SN_0. This gives that:

$$\begin{aligned} \mathrm{BCR}\ (\%) = \mathrm{R_{SN}} &= 130 - 80/[1 + (\mathrm{SN_m} - \mathrm{SN_0})/\mathrm{D_l}] \leq 100 \\ &\quad \text{for } \mathrm{SN_m} \leq \mathrm{SN_0} \\ &= 80/[1 + (\mathrm{SN_0} - \mathrm{SN_m})/\mathrm{D_u}] - 30\ 0 \\ &\quad \text{for } \mathrm{SN_m} < \mathrm{SN_0} \end{aligned} \qquad (2)$$

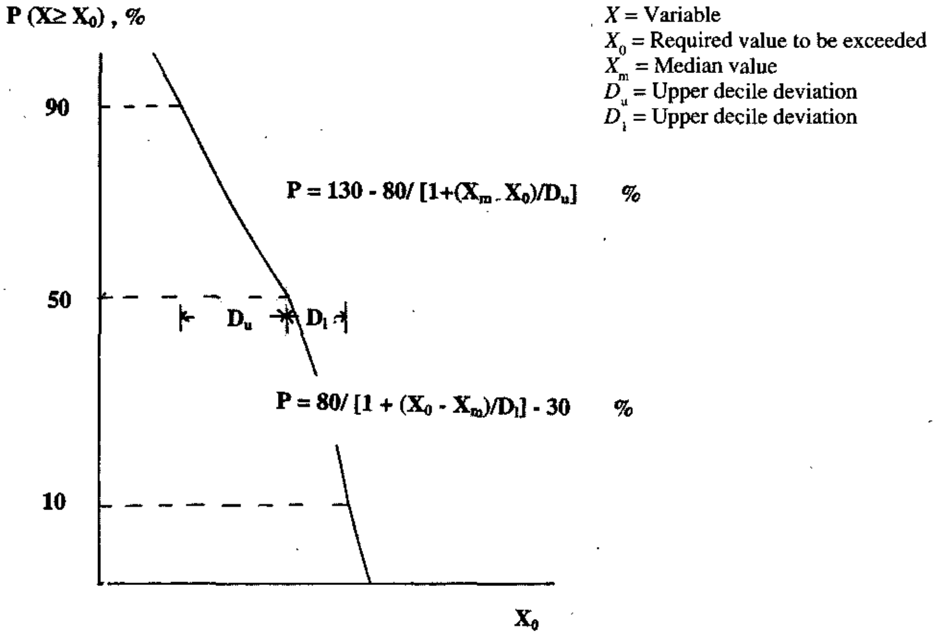

Figure 1. Idealised cumulative-amplitude probability distribution fitted to median and decile deviation values, from Bradley and Bedford, 1976.

where R_{SN} is the probability that the required signal/noise ratio SN_0 is achieved and SN_m. D_l and D_u are respectively the signal/noise ratio monthly median, lower and upper decile deviations from the median.

Hence, the validity of the approach rests both on being able to estimate prevailing propagation and noise factors, and in selecting the required signal/noise ratio. The required signal/noise ratio is a subjective factor depending on what constitutes satisfaction, and this will vary from one listener to another and also depend on the type of transmission system involved. ITU-R(1997b) offers reference values of signal/noise ratio for various types of system. In system and service planning it is also necessary to choose a value of BCR to be achieved, and this too is a subjective factor.

3. BCR FOR A DIGITAL CIRCUIT

Whilst the ionosphere provides a means of signal support with intensities subject to fading, it also gives rise to time spreads associated with multiple propagation paths of differing group lengths and Doppler spreads and shifts attri-

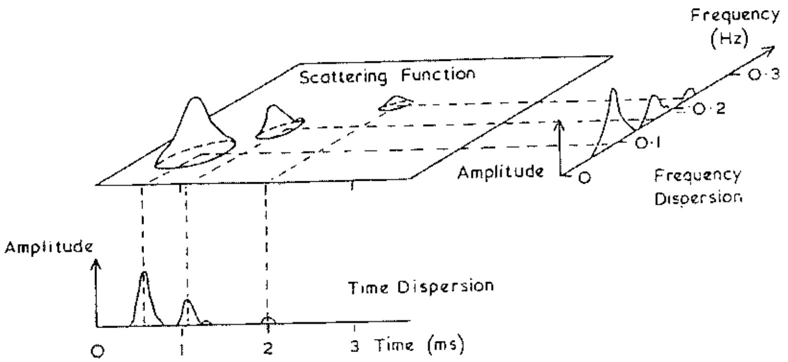

Figure 2. Channel-scattering function for three-moded ionospheric signal propagation, from Vincent *et al.*, 1968.

butable to movements and the growth and decay of ionisation. Vincent *et al.*(1968) introduced the concept of representing such effects in terms of a three-dimensional channel-scattering function. Figure 2, taken from their published work, illustrates the case of a three-moded received signal, in which the separate modes each have different amplitudes, dispersions and shifts. Often in practice, particularly in the presence of scatter propagation when there are ionospheric irregularities present, the various signal components overlap to give continuums both in time and frequency. Especially for high latitude and transequatorial paths dispersions and spreads tend to exceed those arising at middle latitudes (Fig. 3).

Figure 4 is an idealised representation for a particular digital circuit showing the reduction of error rate with increase of median signal/noise ratio SN_m in the presence of dispersion. For low SN_m the error rate is essentially governed by SN_m and falls as SN_m is increased. At some threshold SN_m value depending on the amount of dispersion present a limiting minimum error rate is reached. Increase of the dispersion leads to an increase of that minimum.

In the case of a digital transmission system, in principle system performance is simpler to characterise, because it can be a direct specification of error rate, thereby eliminating human factors, though in practice, as with BCR for an analogue system, there is still the need to decide what percentage of the time, what BCR, constitutes acceptability. A digital system may be impaired by inadequate signal/noise ratio, excessive time spread or excessive frequency dispersion. Whilst the performance of particular systems operating over specific links could be assessed in field trials, it is evident that, as with analogue systems, not all cases could thereby be considered and so again it is necessary to separate the two aspects of characterising the propagation effects from asses-

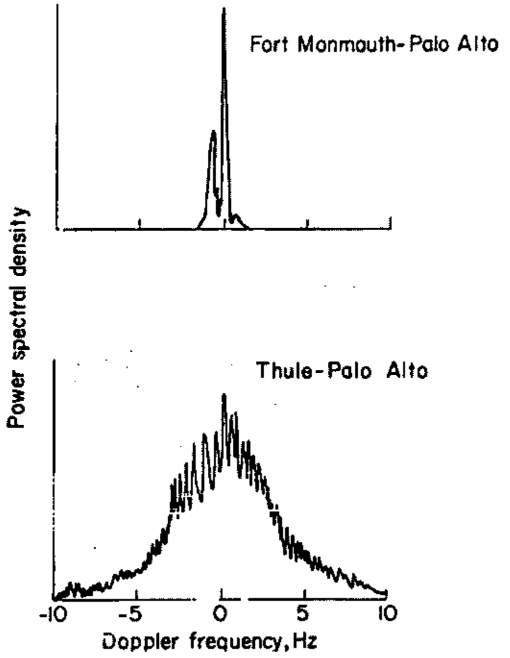

Figure 3. Sample measured Dopler spectra over temperate-latitude path (top section) and transauroral path (lower section), from Vincent *et al.*, 1968.

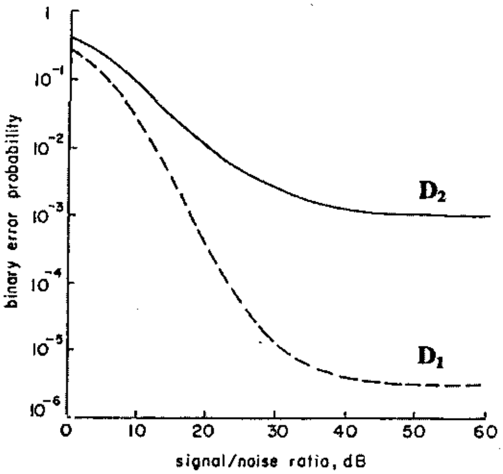

Figure 4. Idealised error probabilities for a digital system in the presence of time spread or frequency dispersions D_1 and D_2 with $D_2 > D_1$.

sing how particular systems respond to these features. The latter can be determined, as in analogue systems, from laboratory tests and ITU-R (1997b) also provides reference values of signal/noise ratio, (but not of parameters of the time spread and frequency dispersion) for some types of digital system. Now it is appreciated that characterising a digital system is more complex, for it becomes necessary to select a finite number of parameters descriptive of the channel-scattering function on which system performance depends, and then to estimate these additional terms, as well as the signal/noise ratio, from propagation considerations.

So, for a digital system not only must a minimum signal/noise ratio be achieved, but also the time spread and frequency dispersion must not exceed limiting values. In the presence of time spread T and frequency dispersion F the BCR becomes a tri-dimensional integral as follows:

$$\mathrm{BCR} = \int_{\mathrm{SN}_0} \int_0^{\mathrm{T}_0} \int_0^{\mathrm{F}_0} \mathrm{P(SN,\ T,\ F)} \cdot dF \cdot dT \cdot d(\mathrm{SN}) \tag{3}$$

T_0 and F_0 are the limiting acceptable T and F for the circuit under consideration. In particular, evaluation of this expression requires a knowledge of the form of P which in general will be unknown. So here in the evaluation method presented it is supposed that dispersion and spread can each be characterised by single values which are independent of SN, and that F and T are also uncorrelated. Then:

$$\mathrm{BCR} = \int_{\mathrm{SN}_0} \mathrm{P}_1(SN)d(\mathrm{SN}) \cdot \int_0^{\mathrm{T}_0} \mathrm{P}_2(T)dT \cdot \int_0^{\mathrm{F}_0} \mathrm{P}_3(\mathrm{F})dF \tag{4}$$

where now P_1, P_2 and P_3 are the probability-density functions with respect to SN, T and F respectively. In particular, eq (4) may be evaluated setting:

$$\mathrm{BCR} = \mathrm{R}_{\mathrm{SN}} \cdot \mathrm{R}_{\mathrm{T}} \cdot \mathrm{R}_{\mathrm{F}} \tag{5}$$

with the separate R's corresponding to the three integrals respectively. Furthermore, with R_{SN} given from eq (2) it is evident that corresponding expressions for R_T and R_F may be formulated in terms of the monthly median, upper and lower decile deviations of the time spread and of the frequency dispersion. Bradley (1997) reviews available information regarding these quantities and stresses the need for additional measurement data. However, empirical expressions are provided for interim use and thereby the BCR may be determined.

4. DISCUSSION

The BCR of a digital system is likely to be influenced by the full channel-scattering function. Time spread and frequency dispersion can only be characterised very approximately by single spread and dispersion parameters. Scattering functions with the same parameter values can be envisaged for which the BCR differs. Nonetheless radio systems engineers are not able at this time to specify other than single spread and dispersion figures that must not be exceeded, and knowledge of ionospheric propagation, largely arising from uncertainties in the prevailing ionisation distributions through which the radio signals must pass, prevents a more complete specification of the channel-scattering function. Use of single spread and dispersion parameters is therefore considered fully justified.

The recommended method of estimating the field strength at a distant receiver of an HF sky-wave signal (ITU-R, 1997c) for path lengths up to 7,000 km involves a modal treatment leading to values of the intensities of a number of simultaneously present propagation modes. It would be possible, in principle, to extend this method to allow for the different time delays of the separate modes, but frequency spread, which also is likely to differ for the separate modes, cannot be evaluated in this way since it requires a knowledge of ionospheric motions and changes, information which at present is unavailable. The accuracy of the recommended field-strength estimates is considered in ITU-R (1997d), where comparisons are presented with reference world-wide measurement data. Typically it has to be accepted that, even with the best available techniques, predictions of the strongest propagation mode can often differ by more than 20 dB from measured values. Predictions of smaller-amplitude modes are likely to exhibit even greater discrepancies. Assuming no errors in the measurements, sources of error in the predictions arise, among other considerations, from incomplete specification of the prevailing ionosphere over the propagation paths and simplifications in modal assessments such as no allowance for F1-mode propagation and no allowance for scatter propagation. Recognition of these difficulties has resulted in a recommended field-strength prediction method for paths beyond 7, 000 km range, where there are a greater number of ionospheric reflections, that is based on empirical allowances, and does not involve a modal treatment. In these circumstances, the use of empirical expressions for time spread and frequency dispersion is considered fully justified.

The evaluation method presented for the estimation of BCR of a digital system supposes that signal/noise ratio, time spread and frequency dispersion are independent factors. Signal/noise ratio is estimated for the strongest propagation mode. Time spread involves the relative delays of multiple modes (or scatter signals). Frequency dispersion arises from ionospheric motions and changes, in the absence of which all received signals would experience zero Doppler shift and spread. This assumption of independence is therefore considered fully justified.

The present time spread and frequency dispersion parameters given by the empirical equations are quoted without regard for signal amplitude, implying a cuboid-shaped scattering function, whereas in practice the width of the scattering function varies relative to the peak amplitude. In these circumstances quoted widths have to be regarded as applying for a certain fixed amplitude below the peak amplitude. However, past measurement data on which the empirical formulations for these parameters are based do not make such a distinction. Measurement data currently being collected (eg Angling *et al.*,1998) provide spread figures between points embracing a fixed percentage of the scattered power. Required tolerable widths need to be defined in the same way as the corresponding modelled quantities. When benign multi-mode propagation occurs, the scattering function consists of separate sharp-peaked components with different mean time delays and frequency shifts and small spreads associated with the different modes; in other situations, particularly those involving scatter propagation, the scattering function is likely to be smeared over a range of times and frequencies, albeit with some superimposed spectral peaks. In these circumstances it is impossible to generalise accurately. The various modulation systems are likely to respond differently to particular scattering functions, but it may be supposed in the case of multi-mode propagation that it is more important to characterise the time delay and frequency dispersion spreads embracing all the principal propagation modes, rather than those associated with a single mode. The problem rests in selection of an amplitude spread parameter relative to the peak amplitude of the strongest mode that embraces all modes that matter. Here then, perhaps somewhat arbitrarily, it is suggested that for planning purposes the tolerable maximum time spread and maximum frequency dispersion be specified between the -10 dB points relative to the peak signal. This assumes that the various presented empirical formulae for estimated spreads and dispersions give compatible figures, which there are grounds to believe is approximately the case.

5. SAMPLE CALCULATIONS OF BCR FOR A DIGITAL CIRCUIT

As an example of a BCR calculation by the proposed formulae for a digital circuit, consider binary differentially coherent phase-shift keying (DCPSK) propagation over a 1,000 km path in Central Europe at a frequency of 6 MHz where the monthly median basic MUF is 10 MHz, where the monthly median signal/noise ratio is 20 dB and the requirement is for a bit error probability of 10^{-3}. This requirement can be taken as corresponding (Fig. 3 of Spaulding, 1982) to a necessary signal/noise ratio of 13 dB. Then from signal/noise considerations alone, Table 2 of ITU-R (1997a) indicates that the lower decile of signal day-to-day variability is 8 dB. So, as an approximation, ignoring here for simplicity the within-an-hour variations of the signals and all noise variations, we can set D_l = 8 dB. Hence, Table 1 of ITU-R (1997a) gives that the BCR is

87%. Then the equations of Bradley (1997) lead to a median time spread of 4 ms and a median frequency spread of $F_m = 0.5$ Hz. Now suppose that the maximum permitted frequency dispersion is $F_0 = 0.45$ Hz, then from the Bradley (1997) equations $D_{Fl} = 0.5$ Hz. and the reliability due to frequency dispersion alone drops to 10%, or from the combined considerations of signal/noise ratio and frequency spread requirements to 9%. The necessity to allow for frequency spread as well as signal/noise ratio in this example is very evident. Other cases can be postulated where also time spread is important to digital systems.

6. CONCLUSIONS

The new method for the calculation of basic circuit reliability for digital systems is shown to be relatively simple to apply and to give more accurate results than using the existing formulae developed for analogue systems. Accuracy will be further improved when additional observational data become available to refine the first-order models of time spread and frequency dispersion that it uses.

REFERENCES

ANGLING, M. J; CANNON, P. S.; DAVIES, N. C.; WILLINK, T. J.; JODALEN, V and LUNDBORG, B. (1998): «Measurement of Doppler and multipath spread on oblique high latitude paths and their use in characterising data modem performance», Radio Science, *33*(1), 97-107.

BRADLEY, P. A. (1997): «Reliability for digital HF radio systems», 7th International Conference on «HF Radio Systems and Techniques», IEE Conference Proceedings *441*, 362-367.

BRADLEY, P. A. and BEDFORD, C (1976): «Prediction of HF circuit availability», Electronics Letters', *12*, 32-33.

ITU-R (1997a): «Computation of reliability and compatibility of HF radio systems», Recommendation P.842, International Telecommunication Union, Geneva.

ITU-R (1997b): «Bandwidths, signal-to-noise ratios and fading allowances in complete systems», Recommendation F.339, International Telecommunication Union, Geneva.

ITU-R (1997c): «HF propagation prediction method», Recommendation P.533, International Telecommunication Union, Geneva.

ITU-R (1997d): «Standardised procedure for comparing predicted and observed HF signal intensities and the presentation of such comparisons», Recommendation P.1148, International Telecommunication Union, Geneva.

SPAULDING, A. D. (1982): «Digital system performance software utilising noise measurement data», NTIA Report 82-95, US Government Printing Office, Washington DC 20402.

VINCENT, W. R.; DALY, R. F. and SIFFORD, B. M, (1968): «Modeling communication systems» in «Ionospheric radio communications in the arctic», Plenum Press, New York.