RECOMMENDATION ITU-R S.738*

Procedure for determining if coordination is required between geostationary-satellite networks sharing the same frequency bands

(1992)

The ITU Radiocommunication Assembly,

considering

a) that FSS networks may share the same frequency bands;

b) that they may cause and experience mutual interference;

c) that this mutual interference can be minimized through coordination;

d) that it is necessary to determine whether there is a need for coordination,

recognizing

that under Article 11 of the Radio Regulations (edition of 1994), the need for coordination is determined by Appendix S8,

recommends

1 that the method given in Annex 1, called the $\Delta T/T$ method, be used to determine if coordination is required between geostationary-satellite networks sharing the same frequency bands;

2 that coordination be required when the calculated value of $\Delta T/T$ of the potentially interfered with network is greater than 6%;

3 that the following Notes will be considered part of this Recommendation:

NOTE 1 – The $\Delta T/T$ method gives an apparent increase in equivalent satellite link noise temperature, and treats the effect of interference as an increase in thermal noise in the wanted network. The power of the interfering signal is assumed to be spread evenly over the frequency bandwidth, with a power density equal to its maximum power density. The ratio $\Delta T/T$ is expressed as a percentage.

NOTE 2 – The above approach is similar to that in Appendix S8 of the Radio Regulations and is applicable with the data provided under Appendix S4 of the Radio Regulations. It also includes additional information to facilitate the application of Appendix S8.

NOTE 3 – The threshold value of 6% is consistent with Appendix S8.

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* Radiocommunication Study Group 4 made editorial amendments to this Recommendation in 2001 in accordance with Resolution ITU-R 44 (RA-2000).

ANNEX 1

Method of calculation for determining if coordination is required between geostationary-satellite networks sharing the same frequency bands

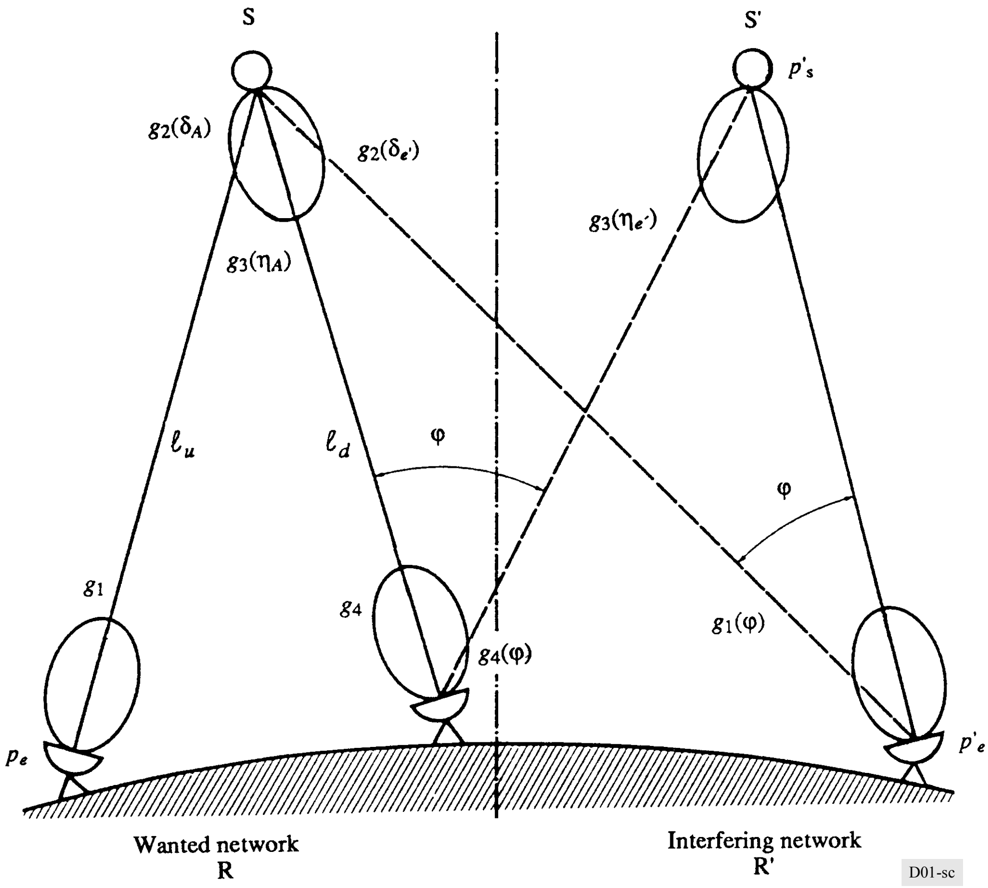
1 Characteristics of networks

Radiocommunication satellites require frequency assignments in two bands, one for the uplink and the other for the downlink. It is current practice for frequency bands to be associated in pairs, one of each pair being used for uplinks and the other for downlinks. Case I below is concerned with the possibility of interference between two systems which have been assigned frequency bands in this way. However, it should be feasible to use a pair of frequency bands in the reverse sense (bidirectional use) for some systems, the uplink band for one network being the same as the downlink band for the network using an adjacent satellite; this is Case II. These two cases cover all relative satellite positions from closely-spaced to near-antipodal positions.

Let A be a satellite link of network R associated with satellite S and A′ be a satellite link of network R′ associated with satellite S′. The symbols such as a, b and c refer to satellite link A and symbols such as a′, b′ and c′ refer to satellite link A′ (see Figs. 1a and 1b).

FIGURE 1a

Geometry - Case I – Wanted and interfering networks sharing the same frequency band in the same direction of transmission



The parameters are defined as follows (for satellite link A):

T: the equivalent satellite link noise temperature, referred to the output of the receiving antenna of the earth station (K);

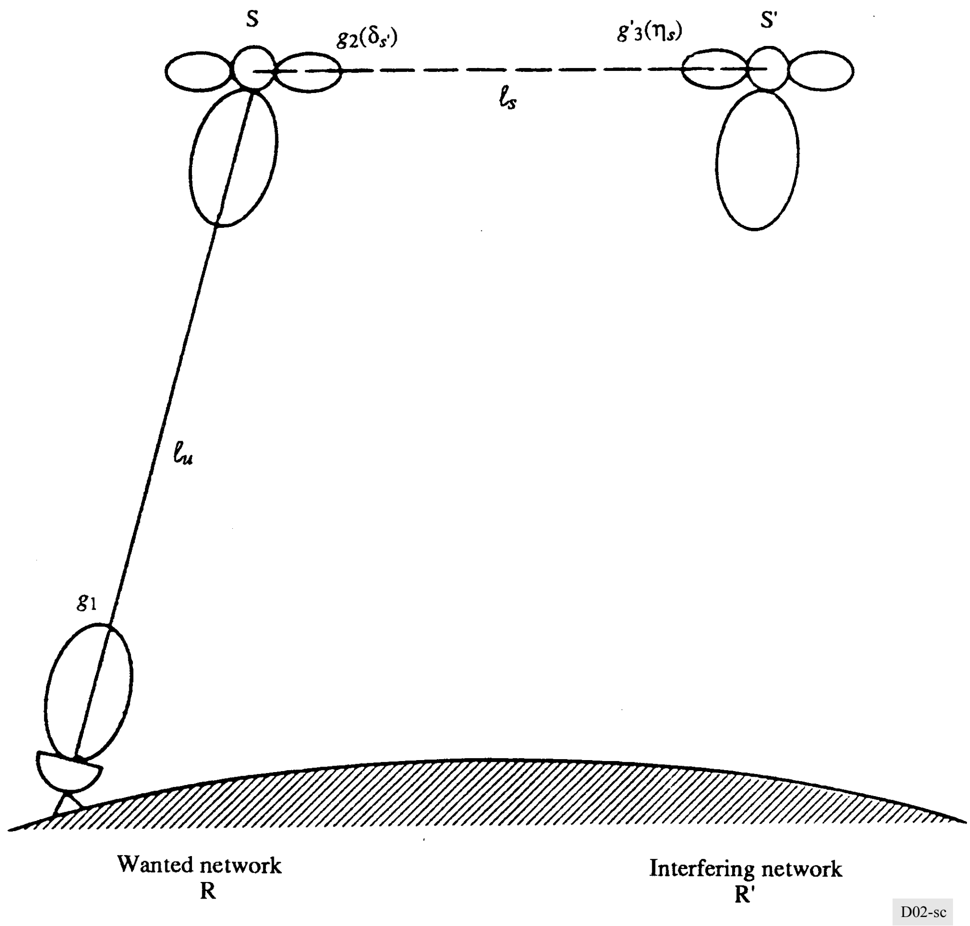
T_s: the receiving system noise temperature of the space station, referred to the output of the receiving antenna of the space station (K);

T_e: the receiving system noise temperature of the earth station, referred to the output of the receiving antenna of the earth station (K);

ΔT: apparent increase in the equivalent noise temperature for the entire satellite link referred to the output of the receiving earth station antenna, caused by interference emissions from other satellite networks;

FIGURE 1b

Geometry – Case II – Wanted and interfering networks sharing the same frequency band in opposite directions of transmission (bidirectional use)



ΔT_s: apparent increase in the receiving system noise temperature of the satellite S, caused by an interfering emission, referred to the output of the receiving antenna of this satellite (K);

ΔT_e: apparent increase in the receiving system noise temperature of the earth station e_R, caused by an interfering emission, referred to the output of the receiving antenna of this station (K);

p_s: maximum power density per Hz delivered to the antenna of satellite S (averaged over the worst 4 kHz band for a carrier frequency below 15 GHz or over the worst 1 MHz band above 15 GHz) (W/Hz);

$g_3(\eta)$: transmitting antenna gain of satellite S in the direction η (numerical power ratio);

η_A: direction, from satellite S, of the receiving earth station e_R of satellite link A;

$\eta_{e'}$: direction, from satellite S, of the receiving earth station e'_R of satellite link A′;

NOTE – The product $p_s g_3(\eta_{e'})$ is the maximum e.i.r.p. per Hz of satellite S in the direction of the receiving earth station e'_R of satellite link A′;

$\eta_{s'}$: direction, from satellite S, of satellite S′;

p_e: maximum power density per Hz delivered to the antenna of the transmitting earth station e_T (averaged over the worst 4 kHz band for a carrier frequency below 15 GHz or over the worst 1 MHz band above 15 GHz) (W/Hz);

$g_2(\delta)$: receiving antenna gain of satellite S in the direction δ (numerical power ratio);

δ_A: direction, from satellite S, of the transmitting earth station e_T of satellite link A;

$\delta_{e'}$: direction, from satellite S, of the transmitting earth station e'_T of satellite link A′;

$\delta_{s'}$: direction, from satellite S, of satellite S′;

$g_1(\varphi)$: transmitting antenna gain of the earth station e_T in the direction of satellite S′ (numerical power ratio);

$g_4(\varphi)$: receiving antenna gain of the earth station e_R in the direction of satellite S′ (numerical power ratio);

φ: topocentric angular separation between the two satellites, taking the longitudinal station-keeping tolerances into account.

NOTE – Only the topocentric angle φ should be used in dealing with Case I;

φ_g: geocentric angular separation in degrees between the two satellites, taking the longitudinal station-keeping tolerance into account.

NOTE – Only the geocentric angle φ_g should be used in dealing with Case II;

k: Boltzmann's constant (1.38×10^{-23} J/K);

ℓ_d: free-space transmission loss on the downlink (numerical power ratio); evaluated from satellites to the receiving earth station e_R for satellite link A;

ℓ_u: free-space transmission loss on the uplink (numerical power ratio); evaluated from the earth station e_T to satellite S for satellite link A;

ℓ_s: free-space transmission loss on the inter-satellite link (numerical power ratio), evaluated from satellite S′ to satellite S;

γ: transmission gain of a specific satellite link subject to interference evaluated from the output of the receiving antenna of the space station S to the output of the receiving antenna of the earth station e_R (numerical power ratio, usually less than 1).

In the foregoing symbols, the gains $g'_1(\varphi)$ and $g_4(\varphi)$ are those of the earth stations concerned. In the event of precise numerical data relating to earth-station antennas not being available, the reference radiation pattern given in Recommendation ITU-R S.465 should be used.

2 Calculation of the equivalent satellite link noise temperature and the transmission gain

2.1 Introduction

The purpose of this section is to provide some guidance for determining, for simple frequency changing transponders, values of equivalent satellite link noise temperatures and transmission gains and in particular the sets of values for:

– the lowest equivalent link noise temperature and the associated transmission gain, and

– the value of transmission gain and associated equivalent link noise temperature that correspond to the highest ratio of transmission gain to equivalent satellite link noise temperature.

The equivalent satellite link-noise temperature T, referred to the output of the receiving antenna of the earth station, and the transmission gain γ of a satellite link using simple frequency-changing transponders, can be determined in several ways.

2.2 General formulation

2.2.1 Method 1

The transmission gain is expressed as follows:

$$\gamma = \frac{p_s g_3(\eta_A) g_4 \,\ell_u}{p_e g_1 g_2(\delta_A)\,\ell_d} \tag{1}$$

where g_1 and g_4 are the maximum (on-axis) transmitting and receiving earth station antenna gains, respectively (see Fig. 1a).

2.2.2 Method 2

The transmission gain is expressed as follows:

$$\gamma = \frac{e.i.r.p._s\ g_4\ BO_i\ 4\,\pi}{W_s g_2(\delta_A)\ \ell_d\ BO_o\,\lambda^2} = \frac{(C/N_0)d}{(C/N_0)u}\ \frac{T_e}{T_s} \tag{2}$$

The equivalent link noise temperature is expressed as follows:

$$T = \frac{(C/N_0)_d}{(C/N_0)_t}\, T_e \tag{3}$$

where:

$(C/N_0)_u$: uplink carrier-to-noise density ratio including only thermal and other background noises (numerical ratio)

$(C/N_0)_d$: downlink carrier-to-noise density ratio including only thermal and other background noises (numerical ratio)

$(C/N_0)_t$: total link equivalent carrier-to-noise density ratio including intra-satellite impairment (intra-satellite interference, intermodulation), thermal and other background noises (numerical ratio)

$e.i.r.p._s$: satellite saturation e.i.r.p. (W)

λ: the wavelength (m) of the uplink frequency

BO_i: transponder input back-off with respect to single carrier saturation (numerical value)

BO_o: transponder output back-off with respect to single carrier saturation (numerical value)

W_s: saturation power flux-density at the satellite (W/m^2).

The product of the satellite saturation power flux-density and the satellite receiving antenna gain (i.e. $W_s \cdot g_2(\delta_A)$) is the same for the satellite antenna beam-peak and beam-edge values. Hence the transmission gain γ is a maximum when the satellite e.i.r.p. is a maximum. This condition occurs at the satellite transmitting antenna beam-peak.

2.3 Derivation of two sets of *T* and γ

2.3.1 Lowest *T* and associated γ

The lowest equivalent link noise temperature, T_{min}, can be expressed as follows:

$$T_{min} = T_e + \gamma_{min} \cdot T_s + T_a \tag{4}$$

where T_a is other internal noise and γ_{min}, its associated transmission gain, is derived from equation (2) by considering the satellite saturation e.i.r.p. ($e.i.r.p._s$) at beam-edge.

2.3.2 *T* and γ corresponding to the highest γ/*T* ratio

The value of γ and associated T that correspond to the highest ratio of transmission gain to equivalent link noise temperature can be determined by maximizing the following equation:

$$\frac{\gamma}{T} = \frac{\gamma}{T_e + \gamma T_s + T_a} \tag{5}$$

This equation is maximized when γ is maximum, i.e. when it is calculated at the satellite antenna beam peak rather than beam edge, consequently:

$$\gamma_{max} = \gamma_{min} \, \Delta g \tag{6}$$

Δg: satellite transmit antenna gain difference between beam-peak and beam-edge values (numerical power ratio).

The associated equivalent link noise temperature is, therefore, given by:

$$T = T_e + \gamma_{min} \, T_s \Delta g + T_a \tag{7}$$

2.4 Summary

The determination of T and γ in accordance with the above-mentioned formulae or by other methods needs to be made for each type of utilization in the satellite network in order to obtain the appropriate sets of values to be used for $\Delta T/T$ calculation.

These methods should not be used to derive values of T and γ from notified or published information by other administrations. Further studies are required concerning these parameters and their relationships.

3 Calculation of the apparent increase in equivalent noise temperature of the satellite link subject to an interfering emission

In order to simplify the calculations, it should be assumed that the basic transmission losses on the space-to-Earth path are identical, regardless of the satellite and earth station considered. Similarly, the basic transmission losses on the Earth-to-space path are assumed to be identical. For each of these two types of path, the losses are calculated using space-to-Earth or Earth-to-space distance of network R′ and the centre frequency of the band shared by the two networks. These assumptions are reasonable in the case of the geostationary-satellite orbit because the difference in loss between the shortest and longest free space paths is only about 1.5 dB.

Case I – Wanted and interfering networks sharing the same frequency band in the same direction of transmission (see Fig. 1a)

The parameters ΔT_s and ΔT_e are given by the following equations:

$$\Delta T_s = \frac{p'_e \, g'_1(\varphi) \, g_2(\delta_{e'})}{k \ell_u} \tag{8}$$

$$\Delta T_e = \frac{p'_s \, g'_3(\eta_e) \, g_4(\varphi)}{k \ell_d} \tag{9}$$

The increase in the equivalent satellite link noise temperature is the result of interference entering at both the satellite and earth-station receiver of link A. When satellites S and S′ are equipped with simple frequency-changing repeaters having the same translation frequency, the interference received by link A is caused on the uplink and downlink by the same link A′.

This can therefore be expressed as follows:

$$\Delta T = \gamma \Delta T_s + \Delta T_e \tag{10}$$

$$\Delta T = \gamma \frac{p'_e \, g'_1(\varphi) \, g_2(\delta_{e'})}{k \ell_u} + \frac{p'_s \, g'_3(\eta_e) \, g_4(\varphi)}{k \ell_d} \tag{11}$$

Hence equation (11) combines the uplink and the downlink interference.

When the translation frequencies of the two satellites are not the same, different links in network R′ may interfere with link A at the satellite and earth-station receivers; let these links be called A′ and $\overline{\text{A}'}$ respectively (the parameters such as $\overline{a'}$, $\overline{b'}$ and $\overline{c'}$ relate to link $\overline{\text{A}'}$). Then:

$$\Delta T = \gamma \frac{p'_e \, g'_1(\varphi) \, g_2(\delta_{e'})}{k \ell_u} + \frac{\overline{p'_s} \, \overline{g'_3}(\eta_e) \, g_4(\varphi)}{k \ell_d} \tag{12}$$

In the same way, the increase $\Delta T'$ in the equivalent noise temperature for the entire satellite link referred to the output of the receiving antenna of the receiving earth station e'_R under the effect of the interference caused by network R is given by the following equations:

$$\Delta T'_{s'} = \frac{p_e \, g_1(\varphi) \, g'_2(\delta_e)}{k \ell_u} \tag{13}$$

$$\Delta T'_{e'} = \frac{p_s \, g_3(\eta_{e'}) \, g'_4(\varphi)}{k \ell_d} \tag{14}$$

When both satellites share the same translation frequency, then:

$$\Delta T' = \gamma' \frac{p_e \, g_1(\varphi) \, g'_2(\delta_e)}{k \ell_u} + \frac{p_s \, g_3(\eta_{e'}) \, g'_4(\varphi)}{k \ell_d} \tag{15}$$

When the two satellites have different translation frequencies (calling two links of the R network A and $\overline{\text{A}}$ and denoting the corresponding parameters $\overline{\text{a}}$, $\overline{\text{b}}$ and $\overline{\text{c}}$):

$$\Delta T' = \gamma' \frac{p_e \, g_1(\varphi) \, g'_2(\delta_e)}{k \ell_u} + \frac{\overline{p_s} \; \overline{g_3}(\eta_{e'}) \, g'_4(\varphi)}{k \ell_d} \tag{16}$$

For the two multiple-access satellites this calculation must be made for each of the satellite links established via one satellite in relation to all of the satellite links established via the other satellite.

If only the uplink or the downlink of the wanted satellite network shares a frequency band with the interfering satellite network, the value for ΔT should be obtained from equation (3) with either ΔT_s or ΔT_e having a zero value, as appropriate.

Case II – Wanted and interfering networks sharing the same frequency band in opposite directions of transmission (bidirectional use) (see Fig. 1b)

Retaining the same notation the noise temperature increase ΔT_s referred to the output of the receiving antenna of the satellite of link A is given by:

$$\Delta T_s = \frac{p'_s \, g'_3(\eta_s) \, g_2(\delta_{s'})}{k \ell_s} \tag{17}$$

The apparent increase in equivalent link noise temperature is then given by:

$$\Delta T = \gamma \Delta T_s \tag{18}$$

The increase $\Delta T'$ in the equivalent noise temperature of the link A′ caused by emissions from the satellite associated with the link A is given by:

$$\Delta T' = \gamma' \, \Delta T'_{s'} = \gamma' \frac{p_s \, g_3(\eta_{s'}) \, g'_2(\delta_s)}{k \ell'_s} \tag{19}$$

If only one band is shared by the two links A and A′, interference between adjacent satellite links will occur only into the link which uses the shared band for its uplink.

Interference between earth stations associated with reverse-frequency assignment links is to be dealt with by coordination procedures analogous to those used for coordination between earth and terrestrial stations.

4 Consideration of polarization isolation

Polarization discrimination could also be used to reduce the probability of interference between satellite networks when different polarizations are used. In this case, the apparent increase in the equivalent satellite link noise temperature could be determined by the following expressions:

– Case I

$$\Delta T = \frac{\gamma \Delta T_s}{Y_u} + \frac{\Delta T_e}{Y_d} \tag{20}$$

– Case II

$$\Delta T = \frac{\gamma \Delta T_s}{Y_{ss}} \tag{21}$$

where the definitions of γ, ΔT_s and ΔT_e have been given previously and Y_u, Y_d and Y_{ss} are the polarization isolation factors (numerical ratio) for the uplink, downlink and inter-satellite link, respectively. Values of the polarization isolation factors are contained in Appendix S8 of the Radio Regulations. These values have been a matter of further study (see Recommendation ITU-R S.736).

Since the polarization isolation factors depend on the types of polarization used by each network and the statistical distribution of orthogonal polarization levels, the polarization isolation factor described above shall be considered only if the polarization has been notified or published as requested in Article 11 of the Radio Regulations (edition of 1994).

5 Comparison between calculated and predetermined percentage increase in equivalent satellite link noise temperature

In order to determine the largest value of $\Delta T/T$ it is necessary to ensure that all potential situations are included. Inter-satellite network interference may be largest in either the uplink or downlink, thus sufficient data should be available to calculate both situations for each space-to-Earth service area and for each projected usage in accordance with Appendix S4 of the Radio Regulations. The $\Delta T/T$ expression is:

$$\frac{\Delta T}{T} = \frac{\Delta T_e}{T} + \frac{\gamma \Delta T_s}{T} \tag{22}$$

when $\gamma \Delta T_s/T >> \Delta T_e/T$, the highest $\Delta T/T$ value occurs when γ/T is maximum. When $\Delta T_e/T >> \gamma \Delta T_s/T$, the highest $\Delta T/T$ occurs when T is minimum. Thus, determinations need to be made using the values of γ and T associated with the maximum value of γ/T and using the minimum value of T and its associated value of γ. The greater of the calculated values of $\Delta T/T$ and $\Delta T'/T'$, expressed as a percentage, should be compared with the corresponding predetermined values. The predetermined values are taken as 6% of the appropriate equivalent satellite link noise temperature (see Radio Regulations, Appendix S8):

– if the calculated value of $\Delta T/T$ is less than, or equal to, the predetermined one, the interference level from satellite link A′ to satellite link A is permissible irrespective of the modulation characteristics of the two satellite links and of the precise frequencies used;

– if the calculated value of $\Delta T/T$ is greater than the predetermined one, a detailed calculation shall be carried out following the methods and techniques set out in ex-CCIR Reports 388 and 455, during the coordination procedure between administrations.

The comparison of $\Delta T'/T'$ with the predetermined value shall be carried out in a similar manner.

As an example, it can be seen that in the case of a satellite link operating in accordance with current ITU-R Recommendations using FM telephony and having a total noise in a telephone channel of 10 000 pW0p including 1 000 pW0p interference noise from terrestrial radio-relay systems and 2 000 pW0p interference noise from other satellite links, a 6% increase in equivalent noise temperature would correspond to up to 420 pW0p of interference noise.

Since, for new networks advance published after 1987, the single-entry interference criterion specified in Recommendation ITU-R S.466 has been increased to 800 pW0p (from 600 pW0p), and the interference noise power in a telephone channel from all other satellite networks to 2 500 pW0p from 2 000 pW0p without frequency re-use (2 000 pW0p from 1 500 pW0p with frequency re-use), the corresponding value of the relative increase in equivalent satellite link noise temperature would be 6% (with frequency re-use) and 6.5% (no frequency re-use) for new networks. For a total noise power in a telephone channel of 10 000 pW0p, including 1 000 pW0p interference noise from terrestrial radio-relay networks and 2 500 pW0p interference noise from satellite networks, 6 and 6.5% increases in equivalent satellite link noise temperature will correspond to interference noise in a telephone channel of 390 and 420 pW0p respectively, if the bandwidth of the interfering carrier is greater than that of the interfered-with carrier. When the interferer has a narrower bandwidth, lower noise increases will result.

6 Procedure for signal-processing transponders

In cases where a change in modulation, or regeneration of the signal, occurs in the satellite, computation of the effects of uplink interference on the total link performance will require special procedures. In some cases, for example analogue signal processing transponders involving signal demodulation and re-modulation, it should be possible to compute an appropriate value for γ which will take into account the signal processing and relate the uplink interference contribution to the downlink. For these cases the calculation would be possible using equation (10) and the modified γ factor.

In other cases, it may not be possible to compute a γ which reasonably accounts for the signal processing in the satellite, such as with digital regenerating transponders. In these cases it will be necessary to treat the uplink and downlink separately, and separate uplink and downlink equivalent link noise temperatures will need to be determined. T_{seq} and T_{eeq} would be values notified independently for the uplink and downlink respectively, T_{seq} being the total uplink equivalent system temperature referred and to the output of the receiving antenna of the earth station. Then $\Delta T_s / T_{seq}$ and $\Delta T_e / T_{eeq}$ will be computed and compared with a predetermined value. This value should be taken as 6% for both the uplink and the downlink, pending further study.

7 Determination of the satellite links to be considered in calculating the increase in equivalent satellite link noise temperature from the data furnished for the advance publication of a satellite network

The greatest increase in equivalent satellite link noise temperature caused to any link of another satellite network, existing or planned, by interference produced by the proposed satellite network must be determined.

The most unfavourable potential transmitting earth station site of the interfering network should be determined for each satellite receiving antenna of the network suffering interference by superimposing the "Earth-to-space" service areas of the interfering network on the space station receiving antenna gain contours plotted on a map of the Earth's surface. The most unfavourable potential transmitting earth station site is the one in the direction of which the satellite receiving antenna gain of the network interfered with, is the greatest.

The most unfavourable potential receiving earth station site of the network suffering interference, should be determined in an analogous manner for each "space-to-Earth" service area of that network. The most unfavourable potential receiving earth station is the one in the direction of which the satellite transmitting antenna gain of the interfering network is the greatest.

Alternatively, the method described in Appendix 1 may be used to account for the most unfavourable earth station locations in determining $\Delta T / T$.

The receiving and transmitting antenna gains cited in the preceding two paragraphs are obtained from the respective antenna radiation patterns requested in Article 11 of the Radio Regulations (edition of 1994) as part of the advance publication procedure. When one or both of the geostationary satellite systems under consideration are in existence, it is preferable that actual measured satellite antenna patterns be utilized. Such measured patterns would permit more realistic assessment of the interference potential in the ensuing calculations.

When the satellite of the network suffering interference is equipped with simple frequency-translating transponders, the above determinations are made in pairs, one for the receiving antenna of a particular transponder and one for the "space-to-Earth" service area associated with the transmitting antenna of that transponder.

The calculation procedure described above may be used to determine the greatest increase in equivalent noise temperature caused to any satellite link in a proposed satellite network by interference produced by any other satellite network.

8 Data to be taken into consideration

To determine the increase in the equivalent satellite link noise temperature, it is necessary to know the correspondence between the uplink bands and the downlink bands. It would also be useful to know, for each frequency band, the number of the repeater and the designation of the beam used.

Moreover, the gain of the space station antennas might be given in the form of a radiation pattern plotted on a representation of the Earth as seen from the satellite. The diagram should indicate the maximum gain at mid-beam and the relative gains at each contour (2, 4, 6, 10, 20, 30 dB, ...). The contour corresponding to the service area should be indicated with a line different from that of the gain contours.

All this information would give a clearer picture of the complete link, thus facilitating the calculation of the apparent increase in its equivalent noise temperature.

9 Consideration of narrow-band carriers

The method of calculation described in this Annex 1 may underestimate the interference from slow swept TV carriers into certain narrow-band (single-channel-per-carrier-SCPC) carriers. Further studies are being conducted within ITU-R to facilitate the accurate prediction of mutual interference between satellite networks under these circumstances (see Recommendation ITU-R S.671).

10 Other considerations

10.1 Clear-air attenuation

Clear-air attenuation or gaseous absorption becomes a significant factor in determining operational parameters as higher frequencies are used. Since it also affects interference paths, it could be included in $\Delta T/T$ calculations. The procedure for accounting for clear-air attenuation needs further definition.

10.2 Link noise temperature in a multi-carrier mode

The inclusion of the effect of multi-carrier operation, including intermodulation, has to be considered for the determination of link noise temperature whenever a network operates transponders in multi-carrier mode. The absence of the intermodulation noise implies a single- or dual-carrier mode which, in turn, implies relatively high-capacity carriers. These high-capacity carriers are adequately protected with somewhat higher ΔT values.

APPENDIX 1

TO ANNEX 1

$\Delta T/T$ calculations for geostationary satellites with unspecified earth-station locations

A method for computing $\Delta T/T$ when earth-station locations are not specifically known is presented as follows.

The topocentric angle φ_t between two satellites is a function of the latitude and longitude of the earth stations with respect to the satellite sub-point. The latitude and longitude determine the geocentric angle ψ between the satellite sub-point and the earth station. As ψ increases, φ_t decreases and the ranges to the two satellites d_1 and d_2 increase. A ratio of topocentric angle φ_t to geocentric angle φ_g may be formed (φ_t/φ_g) as well as the ratios (d_1/d_0) and (d_2/d_0), where d_0 is the distance from the satellite to its sub-point.

The ΔT_s and ΔT_e can be computed by using $G(\varphi_g)$ and d_0 for ℓ_u and ℓ_d and adding a loss $\Delta\ell$ which is:

$$\Delta\ell = 25 \log (\varphi_t/\varphi_g) + 20 \log (d_1/d_0 \text{ or } d_2/d_0) \qquad \text{dB}$$

which assumes the reference 25 log φ earth station side-lobe envelope slope applies. The smallest values of (φ_t/φ_g) occur when earth stations are located on the equator E-W. An orthogonal case is when the earth stations are located on a longitude midway between the satellites N-S. For the E-W case (φ_t/φ_g), d_1 and d_2 were computed using the equations of Annex III of Appendix S8 to the Radio Regulations. As φ_g approaches 0,

$$(\varphi_t / \varphi_g)_{E-W} \approx \frac{42\,166}{d} \cos T \qquad \text{for} \quad d_1 = d_2 = d$$

for earth stations located on the equator, where T is the angle between the earth stations as viewed from the satellite. For the N-S case:

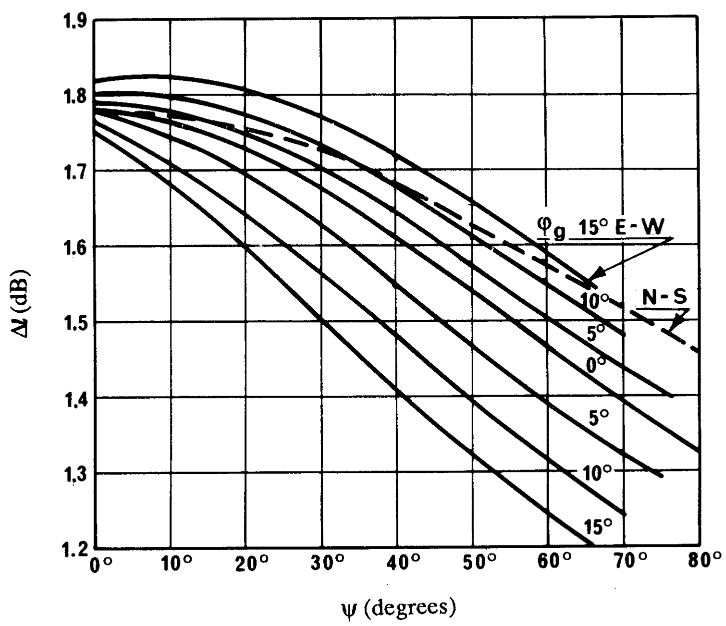
$$(\varphi_t / \varphi_g)_{N-S} \approx \frac{42\,166}{d} \qquad \text{for} \quad d_1 = d_2 = d$$

for φ_g up to at least 15-20° and for earth stations located along the satellite's mid-longitude line.

With these functions, $\Delta\ell$ is computed as a function of ψ for φ_g up to 15° and is shown in Fig. 2. The angle ψ is to the nearest satellite and $(\psi + \varphi_g)$ to the farthest satellite in the E-W plane.

FIGURE 2

Additional interference $\Delta\ell$ path loss as a function of geocentric angle ψ between satellite sub-point and earth station



φ_g : geocentric satellite separation angle

ψ : geocentric angle between satellite sub-point and earth station

$\Delta\ell$: additional interference path loss when 35 796 km is used for free-space loss calculations and earth station off-axis antenna gain is proportional to $-25 \log \varphi_g$

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If up-path interference is associated with d_1 then down-path interference is associated with d_2, or *vice versa*, and thus $\Delta\ell_u$ and $\Delta\ell_d$ are similarly associated. If the earth-station elevation angle H is limited, then the angle ψ is also limited. Approximate functions for $\Delta\ell$ are:

E-W case:

$$\Delta\ell_d \approx A \pm 0.011\ \varphi_g \quad \text{and} \quad \Delta\ell_u \approx A \pm 0.011\ \varphi_g \qquad \text{dB}$$

where:

$$A \approx 1.32 + 0.0065\ H + 0.006\ \varphi_g \qquad \text{dB}$$

for H and φ_g (degrees).

N-S case:

$$\Delta\ell_d = \Delta\ell_u \approx 1.45 + 0.00056\ H + 0.006\ \varphi_g \qquad \text{dB}$$

The values of ψ can be determined by the location of the highest satellite antenna gain values as described in § 4. The $\Delta\ell$ for earth stations located on other than the equator or mid-satellite longitude line can be estimated by extrapolation.