



Transmission of TC-8PSK digital television signals over Eurovision satellite links

System evaluation and optimization

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1. Introduction

Over the past few years, the EBU Technical Department has been studying matters relating to the digitalization of the Eurovision network [1] [2] [3]. These studies resulted from the development of the ETSI Standard, ETS 300 174 [4], which specifies a digital television codec for contribution links at 34.368 Mbit/s (and at 44.736 Mbit/s).

The ETSI digital television codec is directly compatible with Plesiochronous Digital Hierarchy (PDH) terrestrial networks and with the Intermediate Data Rate (IDR) specification (Intelsat Standard IESS-308 [5]) for satellite modems, based on QPSK modulation and rate 3/4 convolutional coding. Proprietary scaled-down versions of this system – at 2×17 Mbit/s and at 8.448 Mbit/s – are available on the market for applications requiring lower picture quality, such as Digital Satellite News Gathering (D-SNG).

The Eurovision Network makes use of Ku-band satellite transponders with a nominal bandwidth of 72 MHz. This is suitable for transmitting two digital signals at 34 Mbit/s in a frequency division

The RAI has carried out a study to optimize the use of 34 Mbit/s digital television contribution links within the Eurovision satellite network. The aim of the study – which was based on computer simulations – was to assess the feasibility of increasing from two to three the number of FDM signals allocated to a 72-MHz satellite transponder – by using the spectrum-efficient TC-8PSK method of modulation.

In this article, the Authors report on the results of the RAI computer simulations.

multiplex (FDM) if QPSK rate 3/4 modulation at a symbol-rate of about 23 Mbaud is adopted. Two EBU Project Groups, N/DIG (Network Digitalization) and N/SAT (Utilization and Optimization of Satellite Capacity), are now evaluating the technical feasibility of increasing from two to three the number of digital television signals that can be carried within a transponder. In order to achieve this, the QPSK rate 3/4 modulation system is replaced by a more spectrum-efficient method of modulation known as *Trellis Coded 8PSK* (TC-8PSK).

The RAI has carried out a computer simulation study to analyse the performance of TC-8PSK mod-

ulation in a Frequency Division Multiple Access (FDMA) configuration of three signals per 72-MHz transponder. In order to maximize the attenuation margin on the up-link and on the down-link, the following characteristics were optimized:

- the forward error-correction (FEC) rate;
- the nominal operating point and the “gain-setting” of the on-board high-power travelling-wave tube amplifier (TWTA);
- the frequency spacing of the three signals;
- the modem filter roll-off.

The results of the RAI computer simulation were then compared with the results obtained by the EBU during its satellite tests on TC-8PSK modulation.

2. Model of the TC-8PSK system

The digital audio/video signal that was analysed (ETS 300 174 [4]) has a useful bit-rate of 34.368 Mbit/s at the output of the encoder. The video components are protected by a Reed-Solomon (R-S) code, RS (255,239), which allows the ETSI codec to produce good picture quality in the presence of an input bit-error rate (BER) of 10^{-4} (after Viterbi decoding). No additional R-S code is inserted in the modem.

In the computer simulations, the audio/video digital source was replaced by a pseudo-random binary source (PRBS).

The simulated TC-8PSK system was based on Pragmatic Trellis Coding [6] rates 2/3 or 5/6. In both cases, a rate 1/2 convolutional encoder was used, with constraint length 7 (64 trellis states) and generator polynomials $g_1 = 133$, $g_2 = 171$ (octal notation).

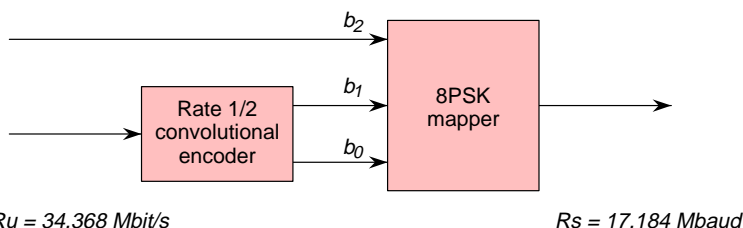


Figure 1
TC-8PSK rate 2/3
modulation and
coding scheme.

Pragmatic Trellis Coding is achieved by associating two coded bits (b_0 and b_1) with one uncoded bit (b_2) to generate an 8PSK symbol (see Fig. 1). Each uncoded bit (b_2) identifies two antipodal 8PSK constellation points, so that the lack of code protection is balanced by the large Euclidean distance in the signal space.

For rate 2/3 Trellis Coding, a group of bits (consisting of one bit at the input of the convolutional rate 1/2 encoder, plus one uncoded bit) generates three transmission bits which are modulated into one 8PSK symbol. The modulator symbol rate¹ (R_s) is equal to half the useful bit-rate (R_u), i.e.:

$$R_s = 1/2 \times 34.368 = 17.184 \text{ Mbaud.}$$

For rate 5/6 Trellis Coding, a rate 3/4 punctured encoder replaces the rate 1/2 encoder of Fig. 1. This time, a group (consisting of three bits at the input of the convolutional encoder plus two uncoded bits) generates six transmission bits which are modulated into two 8PSK symbols. The modulator symbol rate (R_s) is given by:

$$R_s = 2/5 \times R_u = 13.747 \text{ Mbaud.}$$

In the RAI computer simulations, the TC-8PSK modems made use of 3-bit “soft-decision” Viterbi decoding, and of raised cosine filtering, equally split between the transmitter and receiver, with a roll-off of 35 % unless otherwise specified. With

1. The symbol rate corresponds to the signal bandwidth at -3 dB and the demodulator noise bandwidth, B_{RX} .

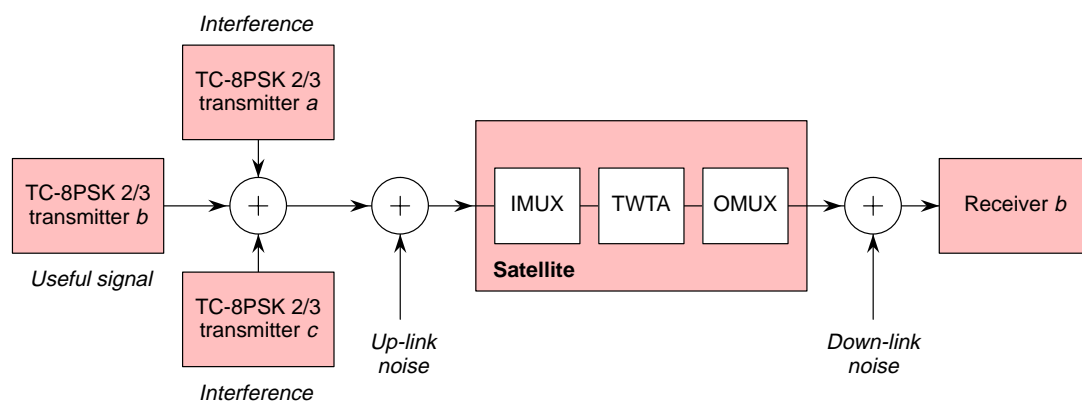


Figure 2
Basic TC-8PSK rate
2/3 satellite link that
was computer-
simulated by the RAI.

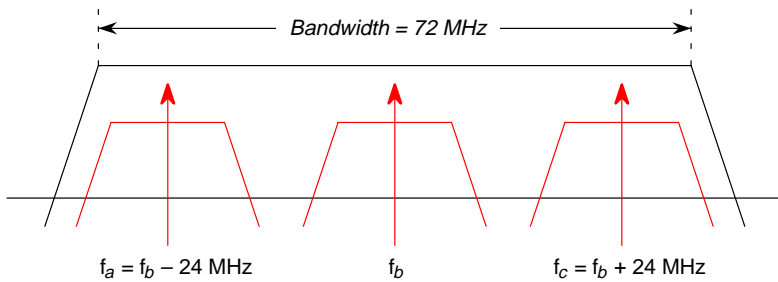


Figure 3
Typical FDM
configuration in the
transponder of
bandwidth 72 MHz.

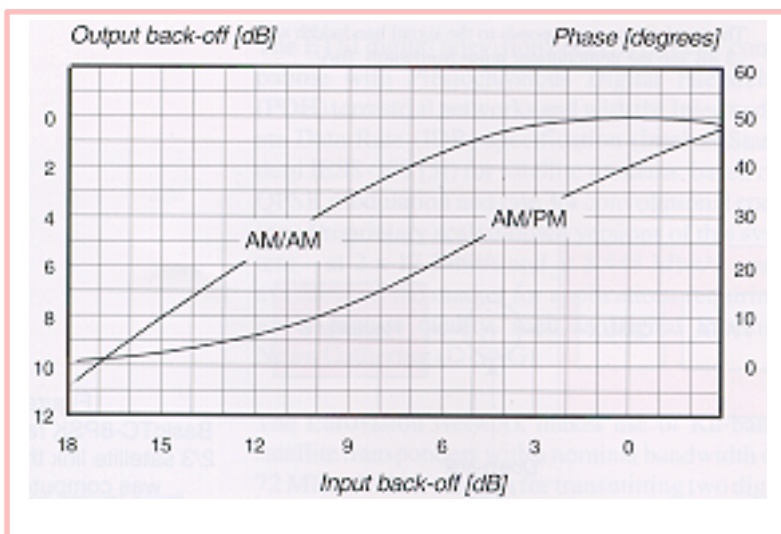
this roll-off, the total bandwidth occupied by 8PSK rate 2/3 modulation is 23.2 MHz; in the case of TC-8PSK rate 5/6, the total bandwidth is 18.6 MHz.

3. Model of the satellite link and frequency plan

The simulated satellite chain is represented in Fig. 2. Three TC-8PSK signals (labelled *a*, *b* and *c*) at a bitrate (R_u) of 34.368 Mbit/s were modulated and combined in the form of a frequency division multiplex (FDM). A frequency spacing (Δf) of 24 MHz was used (see Fig. 3) so that each channel could exploit $1/3$ of the nominal transponder bandwidth of 72 MHz. To simplify the analysis, in some cases only the performance of the central signal (*b*) was studied, while signals *a* and *c* were treated as interference signals.

Fig. 4 gives the AM/AM and AM/PM characteristics of the TWTA, while Fig. 5 shows the frequency responses of the input multiplexer (IMUX) and the output multiplexer (OMUX) which were adopted in the simulations; these responses were at the limit of the transponder “mask” specified by Eutelsat, taking into account also the thermal instabilities. The total usable transponder bandwidth

Figure 4
Simulated TWTA
AM/AM and AM/PM
characteristics.



was of the order of 72 MHz (at the -3 dB points) and the total group delay at the edge of this band was around 50 to 60 ns.

When multiple signals are transmitted in an FDM within a single transponder, the generated TWTA output power is split between the signals according to (i) their input level and (ii) the TWTA AM/AM non-linear characteristic. For the three-signal configuration and TC-8PSK 2/3 modulation system described here, Fig. 6 gives OBO_b (the output back-off of signal *b* with respect to the transponder output saturation power) as a function of IBO_b (the

Abbreviations

AWGN	Additive white Gaussian noise
B_{RX}	Receiver noise bandwidth
BER	Bit error rate
C/N	Carrier-to-noise ratio
E_b/N_0	Noise-margin loss, i.e. the available carrier-to-noise ratio (C/N) in a bandwidth equal to the useful bit-rate of the up-link (R_u)
EIRP	Effective (equivalent) isotropic radiated power
FDM	Frequency division multiplex
FDMA	Frequency division multiple access
FEC	Forward error correction
G/T	Gain/temperature ratio
IBO	Input back-off
IDR	Intermediate data rate
IMUX	Input multiplexer
ISI	Inter-symbol interference
M_d	Down-link margin
M_u	Up-link margin
OBO	Output back-off
OMUX	Output multiplexer
PDH	Plesiochronous digital hierarchy
PRBS	Pseudo-random binary source
QPSK	Quaternary (quadrature) phase shift keying
R_s	Modulator symbol rate
R_u	Useful bit-rate
R-S	Reed-Solomon (code)
SNG	Satellite news gathering
TC-8PSK	Trellis-coded, 8-phase shift keying
TWTA	Travelling-wave tube amplifier
XPD	Cross-polar antenna discrimination

input back-off of signal *b* with respect to the transponder input saturation power). Different IBOs (between 10 dB and 14 dB) were considered for signals *a* and *c*. The results, obtained by computer simulations, refer to a configuration where signals *a* and *c* were modulated (using 8PSK) but signal *b* was unmodulated².

In the reference configuration adopted during the EBU satellite tests on TC-8PSK rate 2/3, namely $IBO_a = IBO_b = IBO_c = 12$ dB, the output back-off of signal *b* was about 7.8 dB.

Fig. 7 shows the spectral power density of the three 8PSK rate 2/3 signals on the up-link, assuming a quasi-linear transmitting station.

3.1. Satellite link budget

A typical satellite link budget was evaluated for the three FDM signals and it will be used in the following Sections as a reference. It relates to clear-sky conditions and involves three classic formulae as given below.

L is the free-space loss of the link, expressed in dB, and E_b/N_o is the available carrier-to-noise ratio (C/N) in a bandwidth equal to the useful bit-rate of the up-link (R_u).

$$L = 20 \log \frac{4\pi D}{\lambda} = 20 \log (f) + 4.15$$

$$\frac{E_b}{N_{o,u,cs}} = EIRP_u - 0.3 - L_u + \frac{(G/T)_s - R_u - K}{(G/T)_s - R_u - K}$$

$$\frac{E_b}{N_{o,d,cs}} = \{EIRP_{d,satur} - OBO\} - 0.2 - \frac{L_d + (G/T)_{rx,cs} - R_u - K}{(G/T)_{rx,cs} - R_u - K}$$

- where
- D = the satellite distance, 38.5×10^6 (m)
 - λ = carrier wavelength (m)
 - f = carrier frequency (Hz)
 - u = up-link
 - d = down-link
 - cs = clear sky
 - s = satellite
 - R_u = reference noise bandwidth for the link budget, corresponding to a useful bit-rate of 34.368 Mbit/s

2. The power of signal *b* was measured at the output of a narrow-band filter (200 kHz) which suppressed the interference from signals *a* and *c*.

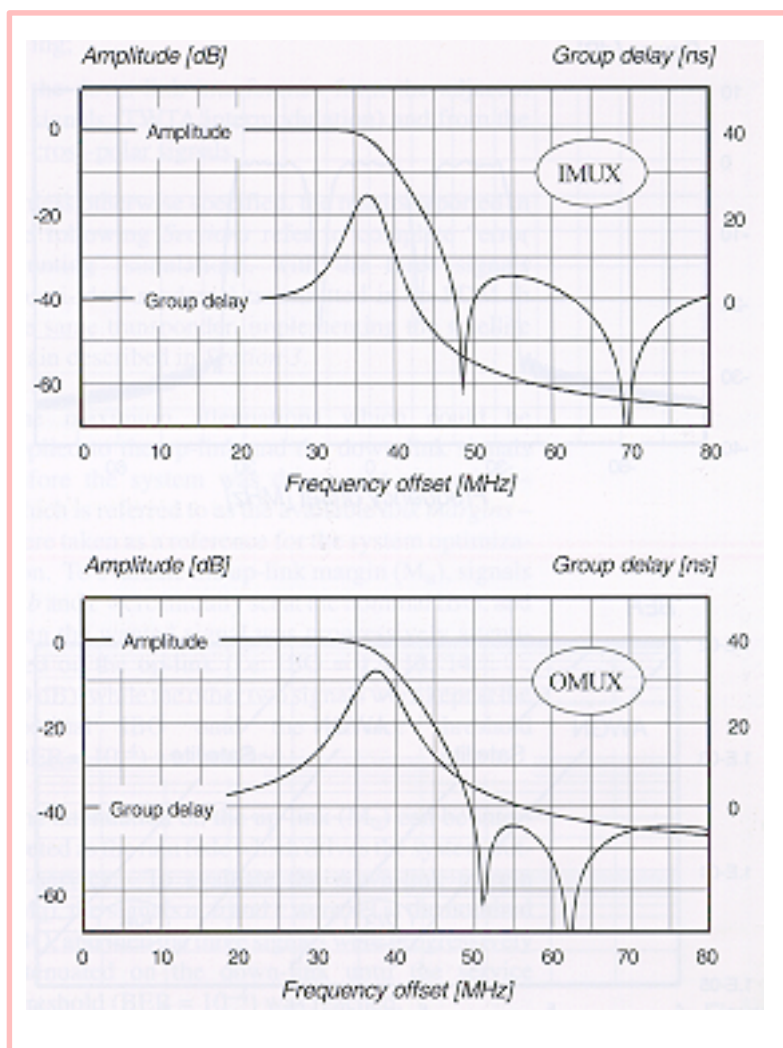


Figure 5
Simulated IMUX and OMUX amplitude and group-delay characteristics.

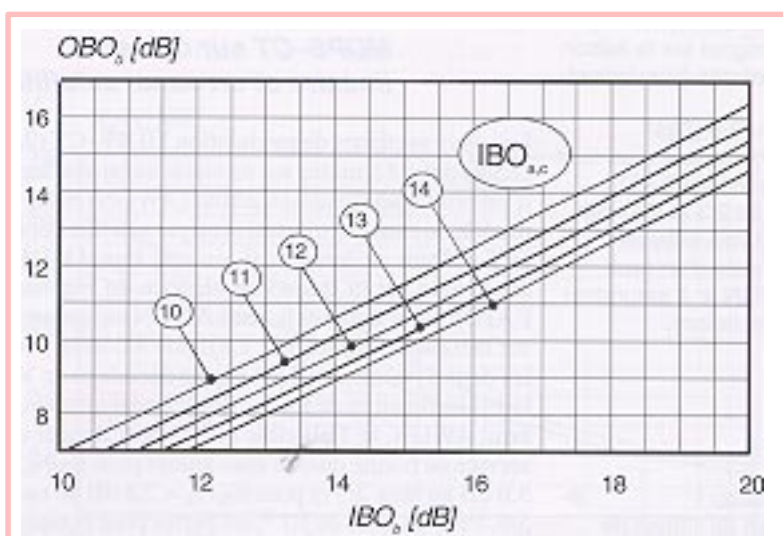


Figure 6
 OBO_b versus IBO_b for different values of $IBO_{a,c}$ (simulation results).

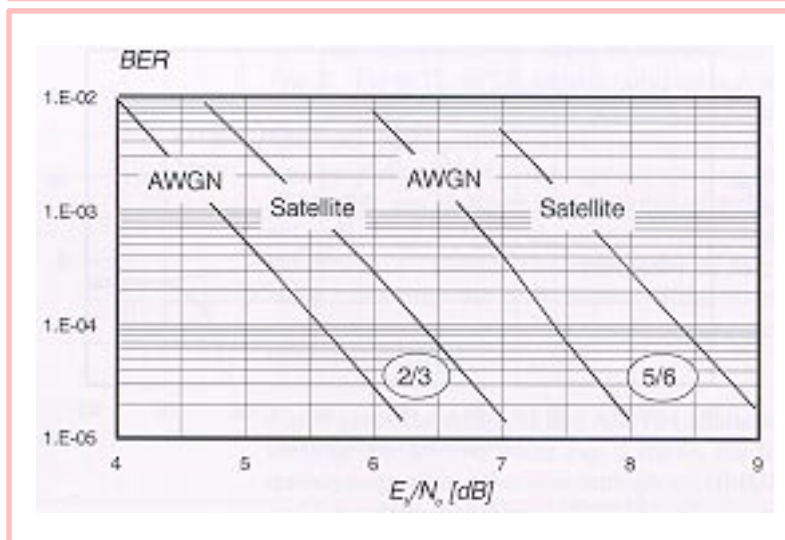
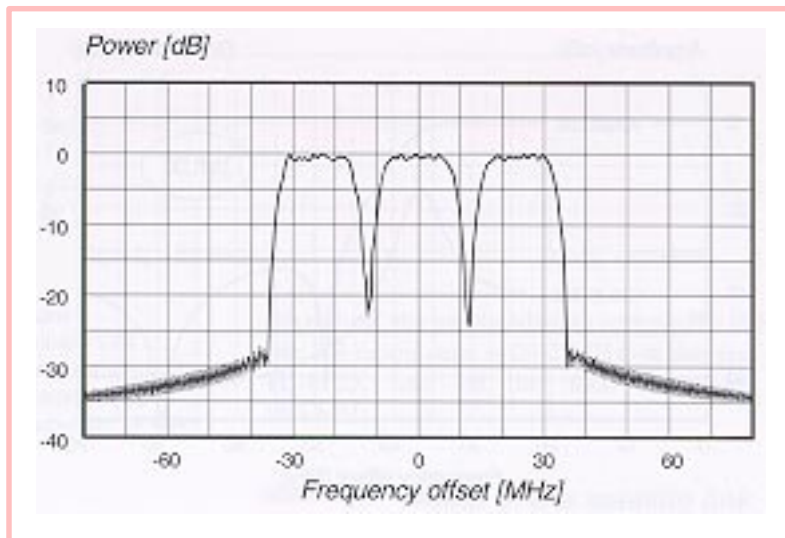


Figure 7 (upper) Signal power spectrum on the up-link (simulation results).

Figure 8 (lower) Performance of a single TC-8PSK signal (rates 2/3 and 5/6) over an AWGN and a saturated satellite channel (simulation results).

Table 1 Reference link budget for an FDM of three signals per transponder.

K = Boltzmann's constant, -228.6 dB (W/HzK)
 satur = saturated TWTA
 OBO = the output back-off of the TWTA
 rx = receiver

Table 1 gives the reference link budget using the above formulae, based on a reference IBO of 12 dB per signal, which was also adopted during the EBU satellite tests on TC-8PSK rate 2/3.

4. Simulation of a single TC-8PSK signal on a linear and a satellite channel

The two TC-8PSK systems with rates 2/3 and 5/6 were simulated on a linear channel affected by additive white Gaussian noise (AWGN), and on the satellite channel model described in Section 3. In the latter case, a single 8PSK signal was located

at the transponder central frequency, with the TWTA in saturation and AWGN on the down-link only. Fig. 8 shows, for both systems, BER (after Viterbi decoding) versus E_b/N_0 . On the AWGN channel, the target BER of 10^{-4} for good service quality was achieved at $E_b/N_0 = 5.6$ dB for rate 2/3 and at $E_b/N_0 = 7.4$ dB for rate 5/6. The noise margin losses introduced by the satellite chain (single signal, TWTA at saturation) at a BER of 10^{-4} were around 0.8 dB for rate 2/3 and 1 dB for rate 5/6.

These losses were mainly due to the TWTA non-linear distortion, since the available transponder bandwidth was very large compared to the signal symbol rate.

Therefore the 25 % spectrum efficiency gain of rate 5/6 coding is associated with a loss of about 2 dB in terms of satellite power efficiency in the presence of noise.

Additional simulations were carried out on a more conventional modulation scheme, QPSK with rate 7/8 punctured convolutional coding, based on the same mother-code as TC-8PSK. At 34.368 Mbit/s, the symbol rate is 19.639 Mbaud and the total bandwidth occupation with a roll-off of 35 % is 26.5 MHz, producing a certain degree of spectrum overlapping in the FDM configuration of Fig. 3. Comparing QPSK rate 7/8 with

Parameter	Value
Noise Bandwidth ($B_{RX} = R_u$) (MHz)	34.368
Reference EIRP of the up-link stations (dBW)	66.3
Up-link frequency (MHz)	14,375
Satellite G/T on the up-link footprint contour (dB(K))	+4.5
Reference satellite IBO per signal at reference $EIRP_u$ (dB)	12
Reference up-link E_b/N_0 in clear sky (dB)	16.4
Satellite saturation EIRP (single signal) on the down-link footprint contour (dBW)	46
Down-link frequency (MHz)	11,075
Reference satellite OBO per signal (see Fig. 6) at reference IBO (dB)	7.8
Reference receive station G/T (dB(K))	35
Reference down-link E_b/N_0 in clear sky (dB)	21.1

TC-8PSK rate 2/3 at a BER of 10^{-4} , the computer-simulations indicated an E_b/N_0 loss of 0.2 dB on the AWGN channel and of 0.3 dB on the saturated satellite channel.

Fig. 9 shows the noise margin loss (with respect to the performance on the AWGN channel) of the systems at a BER of 10^{-4} , for different values of IBO. For large IBOs, the transponder linearity improves and, hence, the noise margin loss tends to become negligible. It should be noted that E_b refers to the effective signal energy on the down-link at the operational OBO, and not to the nominal energy at TWTA saturation point. Therefore the effects of the TWTA power reductions with increasing OBOs are not shown.

The above simulations were based on quasi-ideal modems, with near-perfect demodulation carrier phase, filtering and timing recovery. Therefore a suitable implementation margin should be added to the results to match them to the hardware performance. A direct comparison between the simulation results and the IF-loop performance of commercial TC-8PSK modems indicates typical implementation losses of the order of 1 dB at a BER of 10^{-4} .

5. Simulation of three TC-8PSK signals within a satellite transponder

When three signals are transmitted in an FDM on the same satellite transponder, mutual interference (i.e. intermodulation) takes place in the TWTA, which degrades the system performance – see Fig. A1-1 in Appendix 1. The presence of a non-linearity makes a theoretical analysis quite difficult as the principle of effect superimposition cannot be applied. Also, it is not possible to take measurements on each signal alone, because the TWTA working point is modified when the other two signals are removed. Consequently, a complete simulation of the transmission chain must be carried out for each channel condition (e.g. the IBOs of the three signals, the noise levels).

In order to allow a quick evaluation of the system performance under different conditions, a “simplified analysis” method has been developed by the RAI and is described in Appendix 1. This method is based on splitting the degradation sources into additive independent elements as follows:

- the up-link noise;
- the down-link noise;

- the inter-symbol interference (ISI) produced by the non-linearity and by IMUX/OMUX filtering;
- the down-link interference from the adjacent signals (TWTA intermodulation) and from the cross-polar signals.

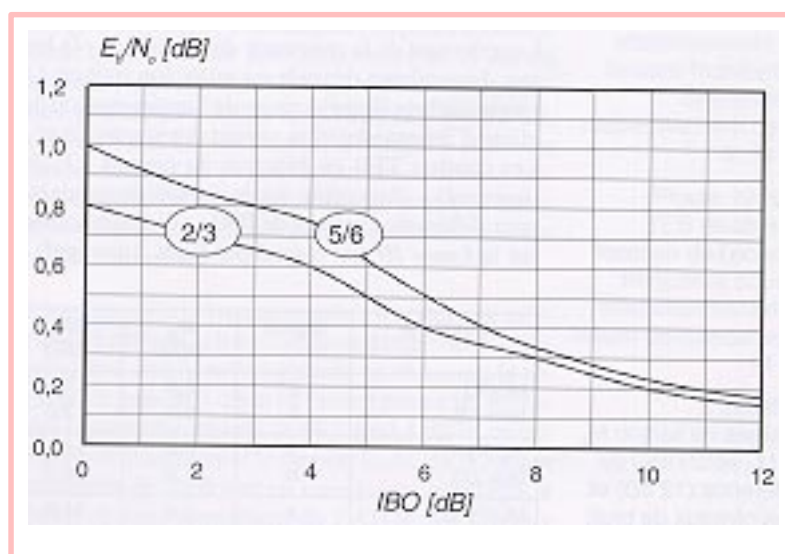
Unless otherwise specified, the results reported in the following Sections refer to complete “error counting” simulations, with the three signals (quasi-ideal modems) transmitted in an FDM in the same transponder, implementing the satellite chain described in Section 3.

The maximum attenuations which could be applied to the up-link and the down-link signals before the system was driven out-of-service – which is referred to as the available *link margins* – were taken as a reference for the system optimization. To evaluate the up-link margin (M_u), signals *a*, *b* and *c* were initially set at the nominal IBO, and then the wanted signal was progressively attenuated on the up-link (i.e. IBO = 12, 13, 14, . . . 20 dB), while the other two signals were kept at the nominal IBO until the service threshold (BER = 10^{-4}) was reached.

The attenuation on the up-link (M_u) can be interpreted as the rain fade which drives the system out-of-service. To evaluate the down-link margin (M_d), the signals *a*, *b* and *c* were set at the nominal IBO, and then the three signals were progressively attenuated on the down-link until the service threshold (BER = 10^{-4}) was reached.

The attenuation on the down-link (M_d) cannot be directly interpreted as a rain fade (since the receiver noise temperature increase is not considered), but rather as a reduction in the G/T of the receiving

Figure 9
Noise margin loss $\Delta E_b/N_0$ versus TWTA IBO (simulation results, single TC-8PSK signal).



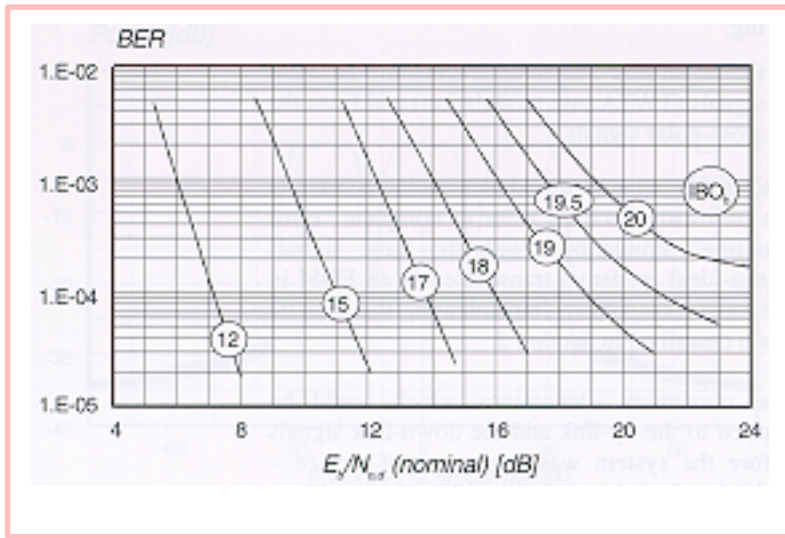


Figure 10
TC-8PSK rate 2/3
performance for an
 $E_b/N_{o,u}$ of 16.4 dB at
 $IBO_b = 12$ dB.

station which drives the system out-of-service in clear-sky conditions.

6. Choice of modulation and coding systems

For TC-8PSK rate 2/3, Fig. 10 shows the results of simulations in which the central signal b was progressively attenuated on the up-link (i.e. $IBO_b = 12, 13, 14, \dots, 20$ dB), while the other two signals (a and c) were maintained at the reference level, $IBO_{a,c} = 12$ dB. The up-link noise power density level was maintained constant, according to the reference link budget of Table 1. While IBO_b was increased, the power of signal b and the available E_b/N_o progressively decreased on both the up-link and the down-link, according to the following relationships:

$$\frac{E_b}{N_{o,u}} = \frac{E_b}{N_{o,u}} (\text{reference}) - \Delta IBO_b \quad (\text{dB})$$

$$\frac{E_b}{N_{o,d}} = \frac{E_b}{N_{o,d}} (\text{reference}) - \Delta OBO_b \quad (\text{dB})$$

where (see Fig. 6):

$$\Delta IBO_b = IBO_b - IBO_b (\text{reference})$$

$$\Delta OBO_b = OBO_b - OBO_b (\text{reference})$$

System	FDM signal	M_u (dB)	M_d (dB)
QPSK rate 7/8	a	5.9	13.1
	b	6.9	13.5
TC-8PSK rate 2/3	a	6.8	14.1
	b	7.5	14.0
TC-8PSK rate 5/6	a	5.0	11.8
	b	5.0	11.0

Table 2
Link margins M_u and M_d for IBO (reference) = 12 dB and noise levels as given in Table 1.

In addition, the power reduction of signal b on the down-link degrades its carrier-to-interference ratio (C/I) due to increasing intermodulation effects caused by signals a and c . Fig. 10 shows curves of BER versus the available E_b/N_o (nominal) on the down-link, for different values of IBO_b . E_b/N_o (nominal) is the available down-link E_b/N_o at the reference IBO of 12 dB, and is proportional to the receiving station G/T^3 .

At high IBO_b levels, the BER curves tend to flatten out, because the up-link noise and the intermodulation effects in the TWTA lead to a non-negligible bit-error ratio, even in the absence of down-link noise. Fig. 10 indicates that, for E_b/N_o (nominal) = E_b/N_o (reference) = 21.1 dB on the down-link, the service threshold (BER = 10^{-4}) is achieved when $IBO_b = 19.5$ dB, corresponding to an up-link margin ($M_u = \Delta IBO_b$) of about 7.5 dB.

Similar simulations have been carried out on the other two systems under study – TC-8PSK rate 5/6 and QPSK rate 7/8 – at the same useful bit-rate of 34.368 Mbit/s and with the same FDM spacing of 24 MHz within the 72 MHz transponder: Table 2 compares the computed up-link and down-link margins of the three systems at a BER of 10^{-4} , in the case where IBO (reference) = 12 dB, both for the central signal b and for the lateral signal a .

The results of the computer simulation compare favourably with the real satellite transmission tests which were carried out by the EBU [1] [2]. During the EBU tests, a complete digital television failure for TC-8PSK rate 2/3 [2] occurred when the up-link EIRP was reduced to about 57.3 dBW; good picture quality (estimated BER of the order of 10^{-4} before R-S) was available at an EIRP_u of 58.3 dB, corresponding to an up-link margin of 8 dB. This experimental result can be compared with the 7.5 dB up-link margin indicated by the computer simulations (see Table 2, signal b), which do not include the modem implementation losses.

Similar results have been obtained with TC-8PSK rate 5/6 when comparing the EBU satellite tests [1] with the RAI simulations.

Taking into account (i) the uncertainties associated with the real satellite characteristics and the link budget during the tests and (ii) the lack of direct BER measurements, it can be concluded that the simulation results are in good agreement with the satellite test results. Since the up-link margin is mainly limited by the up-link noise, an under-estimation of the available E_b/N_o (reference) by

3. When $(G/T)_{RX} = G/T$ (reference) = 35 dB(K), E_b/N_o (nominal) = E_b/N_o (reference) = 21.1 dB (see Table 1).

about 1 to 1.5 dB in *Table 1* could be the origin of the discrepancy between the satellite test results and the computer simulations.

The system offering the best performance in terms of up-link and down-link margins is TC-8PSK rate 2/3; the next best system, QPSK 7/8, offers 1dB inferior performance figures. This degradation is more significant for the lateral signals (*a* and *c*) due to the bandwidth limitations of the satellite IMUX-OMUX filters. Nevertheless in a real transmission environment, the satellite filter characteristics should be less critical than the simulated “mask”, and the lower implementation margin and phase noise sensitivity of QPSK could further reduce the performance difference with respect to TC-8PSK 2/3. The TC-8PSK 5/6 system, when compared with the other two systems, has an intrinsically lower power efficiency (see *Fig. 8*) but an improved resistance to adjacent channel interference. However, on balance, it shows inferior performance to the other two systems.

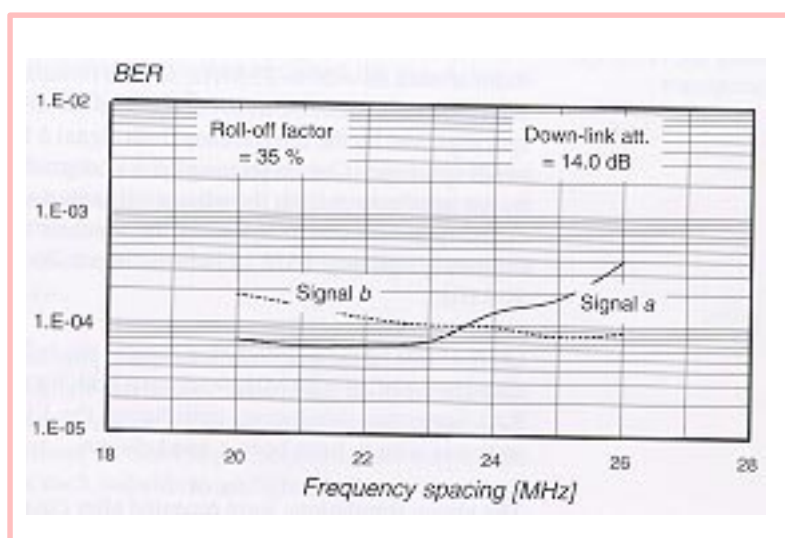
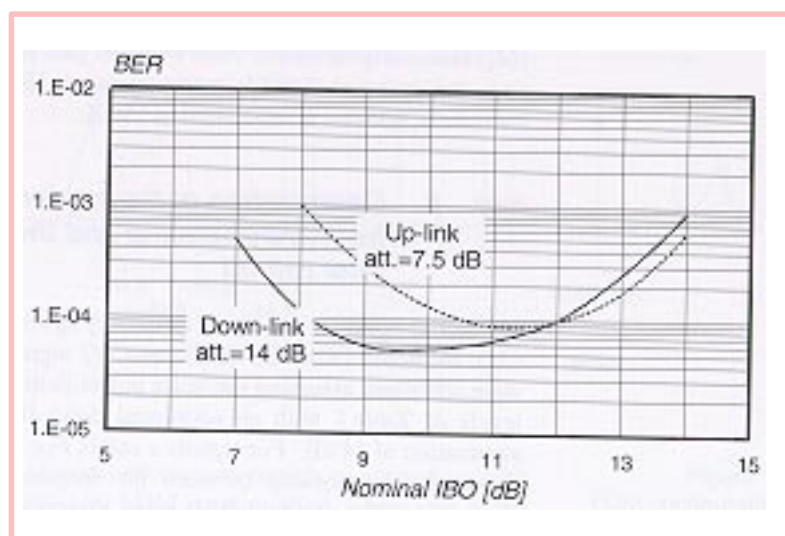
On the basis of these results, only the TC-8PSK rate 2/3 system is further analysed in the following *Sections*.

7. Optimization of the TWTA operating point and the gain setting

In order to optimize the nominal TWTA operating point in clear-sky conditions – i.e. the IBO (nominal) values of the three FDM up-link signals – fixed up-link or down-link attenuations were inserted in the simulations. Also, the residual BERs after Viterbi decoding were measured for different values of IBO (nominal), around the reference IBO of 12 dB (see *Table 1*).

The introduced attenuations were 7.5 dB (up-link) and 14 dB (down-link), corresponding to the computed up-link and down-link margins for a BER of 10^{-4} at the reference IBO of 12 dB (see *Table 2*). For TC-8PSK rate 2/3, *Fig. 11* shows the residual BER as a function of the nominal IBOs, for a constant noise power density which accords with the link budget of *Table 1*.

The simulation results indicate that the residual BER is quite constant around the optimum transponder operating point, corresponding to an IBO of 11 to 12 dB for the up-link margin and 9 to 11 dB for the down-link margin. *Tables A2-1* and *A2-2* in *Appendix 2* report similar results obtained under the same conditions, using the simplified analysis method.



According to the simulation results relating to the down-link margin, an IBO (nominal) of 11 dB could be considered a slightly better choice than the reference one which was adopted during the EBU tests (i.e. IBO = 12 dB, OBO = 7.8 dB). Nevertheless, the down-link margin is not a limiting factor of the link under consideration and, therefore, the reference operating point can be considered a good choice.

The measured up-link margin is significantly lower than the down-link margin; an overall improvement can be expected by reducing the transponder gain setting by 3 dB, and by increasing the EIRPs of the transmit stations from 66.3 dBW to 69.3 dBW. This corresponds to increasing the up-link E_b/N_0 by 3 dB, while keeping constant the TWTA operating point, the signal intermodulation levels and the down-link E_b/N_0 . Under these conditions, the computer simulations have indi-

Figure 11 (upper) Residual BER versus nominal IBO_{a,b,c} for an up-link attenuation of 7.5 dB and a down-link attenuation of 14 dB.

Figure 12 (lower) Residual BER versus frequency spacing for a down-link attenuation of 14 dB.

cated an improvement of about 1.7 dB in the up-link margin (M_u), while the down-link margin (M_d) remains quite stable. Also with this gain setting, the optimum TWTA operating point, IBO (nominal), remains at around 10 to 11 dB.

8. Optimization of the carrier frequency spacing and the filter roll-off

In order to optimize the signal frequency spacing (Δf), the three FDM TC-8PSK rate 2/3 signals were simulated assuming the noise power density levels of *Table 1* with an additional down-link attenuation of 14 dB. For signals *a* and *b*, *Fig. 12* shows the relationship between the frequency spacing and the residual BER after Viterbi decoding.

The BER curve of signal *a* shows a “flat” minimum around $\Delta f = 20$ to 23 MHz, since *a* is mainly affected by the IMUX-OMUX distortions for large spacings, and by the interference from signal *b* for small spacings. Conversely, signal *b* is degraded by the interference from the adjacent signals *a* and *c*, and therefore the BER slowly increases as the frequency spacing (Δf) is reduced from 26 to 20 MHz.

On the basis of these simulation results, the reference choice of $\Delta f = 24$ MHz – adopted both for the RAI computer simulations and during the EBU tests – is seen to have been a good choice.

The above simulations were repeated after changing the raised-cosine filter roll-off in the modem from 35 to 50 %, in order to evaluate the effect of larger signal spectra on the frequency-spacing optimization. The results show that, with a modem roll-off of 50 %, signal *a* suffered from higher degradations only for frequency spacings beyond 24 MHz (due to larger degradations caused by the IMUX-OMUX filters), while the performance of signal *b* remained unaltered. Therefore the transmission of three TC-8PSK rate 2/3 signals, with a frequency spacing of 24 MHz, is not sensitive to

the choice of the modem roll-off in the range 35 to 50 %.

9. Effects of cross-polar interference and alternative FDM configurations

The link margins have been evaluated under the noise levels given in *Table 1*, also in the presence of cross-polar interference on the up- and down-links, assuming two levels of cross-polar discrimination (XPD):

$$XPD_u = XPD_d = 30 \text{ dB}$$

$$XPD_u = XPD_d = 25 \text{ dB.}$$

The up-link margin evaluation was based on the assumption that the rain attenuation only affects the wanted signal and not the cross-polar interference, which is transmitted from a different location. Conversely, the down-link margin evaluation assumed that both the wanted and the interfering signals would be attenuated. For simplicity, the XPD variations due to fading were not taken into account.

The results obtained by the simplified analysis method described in *Appendix 1* are given in *Table A2.2* of *Appendix 2*. For a reference IBO of 12 dB and an XPD of 30 dB, the presence of the cross-polar interference produced negligible reductions in the up-link and down-link margins. For an XPD of 25 dB, the degradation was 0.9 dB on the up-link and 0.4 dB on the down-link. The optimum nominal TWTA operating point remained at an IBO of around 10 to 11 dB.

Finally the up-link and down-link margins were evaluated for an FDM configuration in which a 34-Mbit/s TC-8PSK rate 2/3 signal was replaced by four QPSK signals comprising two Euroradio signals at 2 Mbit/s (coding rate 1/2) and two SNG signals at 8 Mbit/s (coding rate 3/4). *Fig. 13* shows the frequency position of each signal inside the multiplex, while *Table 3* summarizes the main

System	Bit-rate (Mbit/s)	Δf (MHz)	IBO (dB)	OBO (dB)	$E_b/N_{o,u}$ (dB)	$E_b/N_{o,d}$ (dB)
QPSK 1/2	2.048	-34.5	21.0	18.7	19.6	22.4
QPSK 1/2	2.048	-31.5	21.0	17.8	19.6	23.3
QPSK 3/4	8.448	-25.5	18.0	14.0	16.5	21.0
QPSK 3/4	8.448	-16.5	18.0	13.9	16.5	21.1
8PSK 2/3	34.368	0.0	12.0	7.5	16.4	21.4
8PSK 2/3	34.368	24.0	12.0	7.6	16.4	21.3

Table 3
FDM system parameters with four QPSK signals replacing one 8PSK signal.

system and transmission parameters: modulation bit-rate, frequency position relative to the centre of the 72-MHz transponder channel, IBO, OBO, $E_b/E_{o,u}$ and $E_b/E_{o,d}$. The E_b/E_o figures include the attenuation due to the IMUX and OMUX filters.

The up-link and down-link margins, evaluated by complete computer simulations at a BER of 10^{-4} without modem implementation losses, are given in Table 4. Comparing the above results with those of Table 2 (relevant to three 8PSK rate 2/3 signals), it can be deduced that the four QPSK signals do not degrade the performance of the remaining two 8PSK signals. In addition, the two QPSK rate 3/4 signals have similar margins as the 8PSK signals, while the QPSK rate 1/2 signals have significantly larger margins.

10. Conclusions

The results of computer simulations carried out at the RAI Research Centre, within the framework of the optimization of the Eurovision network, are in good agreement with the results of laboratory tests (modem IF-loop tests) and with the results of EBU satellite test transmissions [1][2]. The difference between the computer simulation and the satellite test results (1 to 1.5 dB, depending on the transmission configuration) mainly arises from the uncertainties that were evident on the link budget during the satellite tests and on the characteristics (TWTA, IMUX and OMUX) of the real satellite chain.

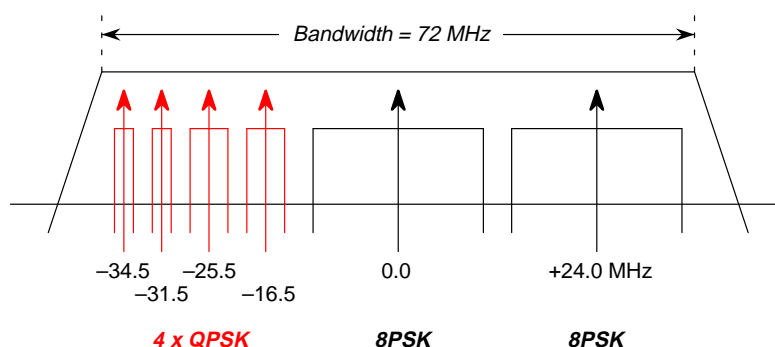
Three channel coding and modulation systems have been analysed:

- pragmatic TC-8PSK rate 2/3;
- pragmatic TC-8PSK rate 5/6;
- QPSK with convolutional coding rate 7/8.

The simulations indicate that, in the FDM configuration of three signals per 72 MHz transponder, the TC-8PSK rate 2/3 modulation offers the best up-link and down-link margins, followed within 1 dB by QPSK rate 7/8. The optimizations of the TC-8PSK 2/3 signal levels in the TWTA (nominal IBOs under clear-sky conditions) and of the frequency spacing (Δf) of the signals have confirmed that the correct choices were made during the EBU tests, namely:

$$\begin{aligned} \text{IBO (nominal)} &= 12 \text{ dB} \\ \Delta f &= 24 \text{ MHz} \end{aligned}$$

For this frequency spacing, the system performance is not sensitive to modem roll-off factors in the range 35 to 50 %.



Additional simulations have been carried out with a different FDM configuration, where one of the 8PSK rate 2/3 signals was replaced by two Euro-radio signals (QPSK rate 1/2 at 2 Mbit/s) and two SNG signals (QPSK rate 3/4 at 8 Mbit/s). These simulations have demonstrated the feasibility of the 8PSK rate 2/3 transmission mode.

Figure 13
FDM configuration with four QPSK signals replacing one of the 8PSK signals in the satellite transponder.

On the basis of this analysis, an increase from two to three in the number of digital television signals carried within each 72-MHz Eurovision transponder seems feasible from a technical point of view.

The simplified analysis method described in Appendix 1 can be used to estimate the system performance under different operational conditions, without the need to perform complete simulations for each individual configuration.

System	Δf (MHz)	M_u (dB)	M_d (dB)
QPSK 1/2	-34.5	10.4	18.3
QPSK 1/2	-31.5	11.1	19.3
QPSK 3/4	-25.5	7.6	15.6
QPSK 3/4	-16.5	6.9	15.4
8PSK 2/3	0.0	7.4	14.4
8PSK 2/3	24.0	7.1	14.2

Table 4
Up-link and down-link margins (without modem implementation loss).

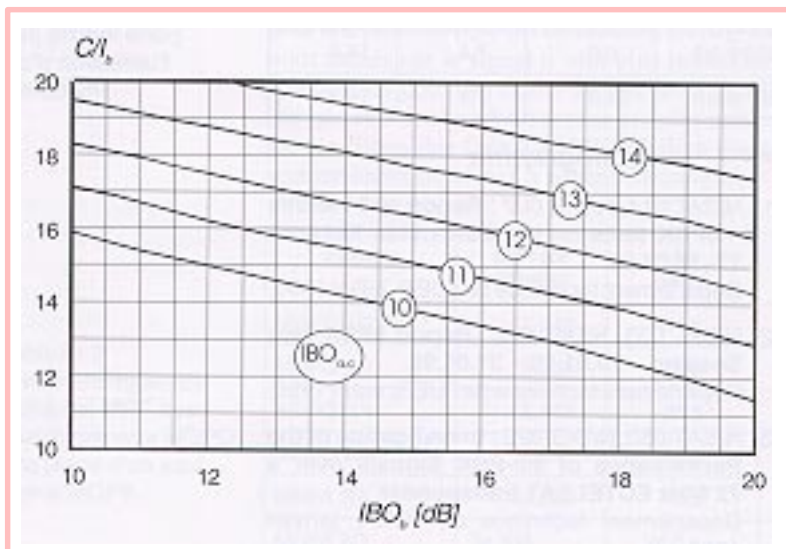
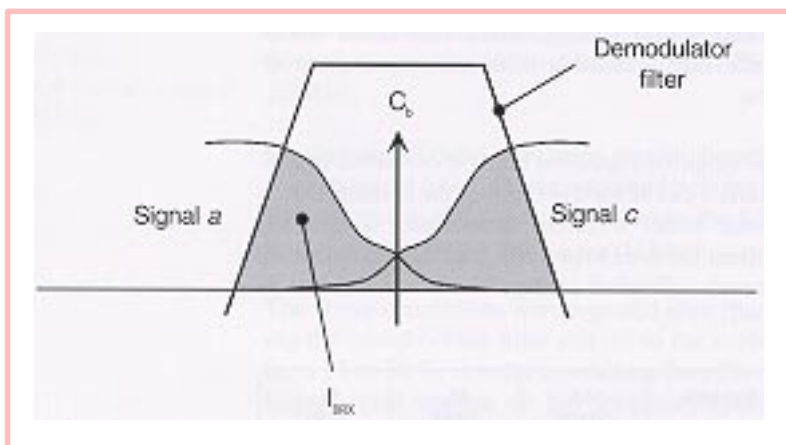
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Figure A1-1 (upper)
Measurement of the interfering power I_{BRX} in the demodulator filter.

Figure A1-2 (lower)
 C/I_b versus IBO_b for different values of $IBO_{a,c}$ (simulation results).



Appendix 1

Simplified analysis method

A simplified analysis method has been developed by the RAI in order to allow a first estimation of the system performance under different operating conditions (e.g. up-link EIRP, nominal TWTA input back-off, noise power density levels), without the need to perform complete computer simulations. The analysis method is focused on the central signal b of the three-carriers-per-transponder configuration which uses TC-8PSK 2/3 modulation and a carrier spacing of 24 MHz.

In the simplified analysis method, the following sources of signal degradation are considered:

g) Gaussian noise

Neglecting the noise compression on the satellite TWTA, the assumption is made that up-link and down-link noise of equal power have the same effect on the system BER, and their power levels can be added.

h) Interference (intermodulation) from adjacent signals in the FDM

Since the channel spacing of 24 MHz is larger than the total signal bandwidth, including the roll-off (e.g. $17.184 \times 1.35 = 23.198$ MHz in the case of 8PSK rate 2/3 modulation), the mutual interference between the three 8PSK signals on a quasi-linear up-link is negligible.

On the down-link, the equivalence and additivity of noise and interference is assumed. In other words, an interfering signal of power I_{BRX} (in the receiver bandwidth) is assumed to produce the same BER as a Gaussian noise of equal power (i.e. $N_{BRX} = I_{BRX}$).

This approximation neglects the fact that the intermodulation amplitude is not Gaussian and that it is correlated with the signal itself. It should be noted that the noise and the interference contributions must be evaluated and added after the demodulator receiving filter (with noise bandwidth B_{RX} equal to the symbol rate).

A practical problem is how to measure the interference power (I_{BRX}) in the demodulator filter without removing the useful signal and modifying the TWTA working point.

In the RAI computer simulations, while the interfering signals a and c were modulated, the wanted signal b was un-modulated (see Fig. A1-1). The

Step	What to evaluate	Formulae, Constants & Figures to use
Evaluation of the <i>required</i> C/N+I in B _{RX}		
1	Required E _b /N ₀ on AWGN at BER = 10 ⁻⁴	From Fig. 8 (AWGN curve)
2	Modem implementation loss	≈ 1 dB
3	IBO _{tot}	Add TWTA input powers
4	ISI noise margin loss on TWTA at IBO _{tot}	From Fig. 9
5	Required E _b /N ₀ by satellite at IBO _{tot}	Combine results from Steps 1, 2, 4
6	Required C/N+I by satellite in B _{RX} for 8PSK 2/3	C/N+I = E _b /N ₀ + 10 Log (R _u /B _{RX}) = E _b /N ₀ + 3 dB
Evaluation of the <i>available</i> C/N+I in B _{RX}		
7	OBO _b versus IBO _a , IBO _b , IBO _c	from Fig. 6
8	Available C/N _u and C/N _d in B _{RX} , at IBO _b and OBO _b	From link budget (Table 1) E _b /N _{0,u} = E _b /N _{0,u} (reference) – ΔIBO E _b /N _{0,d} = E _b /N _{0,d} (reference) – ΔOBO E _b /N _{0,u} (reference) = 16.4 dB E _b /N _{0,d} (reference) = 21.1 dB IBO (reference) = 12 dB OBO (reference) = 7.8 dB C/N = E _b /N _{0,tot} + 3 dB
9	C/I _d (b) (intermodulation) in B _{RX} at IBO _{a,b,c}	From Fig. A1.2
10	Available C/(N _u +N _d +I _u +I _d)	Combine results from Steps 8 and 9

Table A1-1
Simplified analysis
method.

Note: If C/N+I (available) > C/N+I (required), the service quality is guaranteed.

IBO _{a,b,c} nominal	XPD = ∞		XPD = 30 dB		XPD = 25 dB	
	M _u	M _d	M _u	M _d	M _u	M _d
5	6.0	13.6	5.5	13.5	4.8	13.1
6	6.7	14.0	6.3	13.8	5.5	13.5
7	7.2	14.4	6.9	14.3	6.2	14.0
8	7.8	14.5	7.4	14.4	6.7	14.1
9	8.2	14.6	7.8	14.5	7.1	14.2
10	8.3	14.6	8.0	14.5	7.3	14.2
11	8.2	14.4	7.9	14.3	7.3	14.1
12	7.9	14.0	7.7	13.9	7.1	13.7
13	7.5	13.6	7.3	13.5	6.8	13.3
14	6.9	13.0	6.7	12.9	6.3	12.7

IBO _{a,b,c} nominal	XPD = ∞		XPD = 30 dB		XPD = 25 dB	
	M _u	M _d	M _u	M _d	M _u	M _d
5	3.7	11.3	3.4	11.1	2.8	10.4
6	4.8	12.0	4.4	11.8	3.7	11.2
7	5.5	12.6	5.2	12.4	4.4	12.0
8	6.3	12.9	5.9	12.7	5.2	12.3
9	6.8	13.1	6.4	12.9	5.6	12.6
10	7.0	13.1	6.6	13.0	6.0	12.7
11	7.0	13.1	6.7	12.9	6.0	12.7
12	6.7	12.6	6.5	12.5	5.8	12.2
13	6.4	12.3	6.1	12.2	5.5	11.9
14	5.8	11.6	5.6	11.5	5.1	11.2

Table A2-1 (left)
Up-link and down-
link margins (dB) of
signal *b* versus
nominal IBOs
(without modem
implementation loss).

Table A2-2 (right)
Up-link and down-
link margins (dB) of
signal *b* versus
nominal IBOs
(including modem
implementation loss
of 1 dB).

parameter C_b corresponds to the TWTA saturation power attenuated by OBO_b . Fig. A1-2, obtained by computer simulations, shows the C/I_b curves for the central signal (b) versus IBO_b , for different values of $IBO_{a,c}$. A nominal channel spacing of 24 MHz was adopted according to Fig. 3.

i) Inter-symbol interference

The inter-symbol interference (ISI) produced by the TWTA non-linearity depends on the working point (IBO) that is determined not only by the signal itself but also by the other signals that are multiplexed in the transponder. For a single carrier, the noise margin loss with respect to the AWGN channel ranges from 0 dB (high back-offs, quasi-linear TWTA) to about 0.8 dB (saturated TWTA, single carrier) (see Fig. 9). In the simplified analysis developed by the RAI, it is assumed that the ISI degradation in the FDM configuration is the same as for the single signal configuration – for the same total IBO. IBO_{tot} refers to the power sum of the three input signals.

j) Cross-polar co-channel digital interference

It is assumed that cross-polar co-channel digital interference has similar effects on the system BER as Gaussian noise of equal power in the receiving filter. When the cross-polar transponder carries the same signal configuration as the wanted transponder, the interference power (I) is equal to the

wanted power (C) attenuated by the cross-polar antenna discrimination (XPD): i.e. $C/I = XPD$.

The simplified analysis method adds all the interference, intermodulation and noise power contributions (measured within the receiver filter bandwidth) in order to evaluate the available C/N+I ratio on the satellite links, and compares it with the C/N+I ratio required by the modulation system to deliver the target BER of 10^{-4} . The service continuity and quality is assured when $C/N+I$ (available) > $C/N+I$ (required).

The detailed computation procedure is summarized in Table A1-1.

Appendix 2

Link margin evaluation by means of the simplified analysis method

The link margins, as defined in Section 5, have been evaluated with the simplified analysis method, without cross-polar interference (i.e. $XPD = \infty$) and with cross-polar co-channel interference of 25 dB and 30 dB, both on the up-link and the down-link. The noise power density levels correspond to the reference link budget of Table 1.

Tables A2-1 and A2-2, respectively, show the results without and with modem implementation losses.



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