Wide RF-band digital HDTV emission systems – Peformance of advanced channel coding and modulation techniques *

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The perspectives of wide RF-band digital HDTV emission systems (W-HDTV) via satellite in the 20-GHz range, capable of providing near-studio quality, are examined in the light of the current progress on bit-rate reduction algorithms based on hybrid discrete-cosine transforms (DCT) and of advanced modulation and channel coding techniques.

These W-HDTV systems are evaluated, for different bit-rates (140, 105 and 70 MBit/s), in the context of a possible "common frequency allocation" of the frequency range 21.4-22 GHz; this would allow very efficient use of the spectrum by assigning the overall bandwidth to all service areas. The systems are compared by computer simulations and laboratory evaluations, over a typical satellite channel affected by co-channel and adjacent-channel interference.

An example for a W-HDTV broadcasting satellite service at 22 GHz in climatic zones K and L confirms the suitability of the proposed systems for operation in regions affected by severe propagation conditions.

1. Introduction

Over the last few years high-definition television (HDTV) has become the major advance in the world of telecommunications. HDTV techniques are already widely used in electronic film and television production. Moreover, the penetration of direct satellite broadcasting and the evolution of domestic receivers offer new opportunities for HDTV services addressed to the home. In Europe, HD-MAC is the candidate for the first HDTV services at 12 GHz, on "narrow RF-band" satellite channels (27 MHz). In the longer term, when source and display technologies improve, a service able to deliver the picture quality inherent in the studio standard, with a number of channels per service area which is higher than that allocated by the WARC'77 Plan, will become attractive.

In order to meet these objectives "wide RF-band" satellite channels are required. The possible allocation of a new frequency band for these future services is an important target of the WARC'92 Conference in Spain. In accordance with Resolution 521, this new frequency band should be found in the range 12.7 to 23 GHz, although there is a general preference, at least in Region 1, for an allocation

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covering the frequency range 21.4 to 22 GHz, possibly on a world-wide basis. Taking into account the time-scale required for frequency planning, after the WARC'92, a "full digital solution" appears as the most appropriate for the implementation of these future high-quality HDTV systems.

Digital techniques are now recognized as the way of the future. As a result of the use of digital processing and increased display resolution, the television and computer industries are progressively merging and the commercial use of HDTV and digital technology is rapidly developing. From a technical point of view, the remarkable progress on bit-rate compression, digital modulation and channel coding techniques, based on soft-decision Viterbi decoding, are such that a progressive conversion can be expected from analogue to digital transmission technology on communication satellite circuits used for HDTV programme exchange and distribution.

HDTV satellite emission systems in the 20-GHz range have to be designed in such a manner as to ensure that they can cope with the adverse propagation characteristics existing throughout this part of the spectrum, typified by high attenuation due to rain, low cross-polar discrimination (XPD), gaseous absorption, etc. The adoption of a digital solution offers superior performance and significant advantages over analogue solutions based on frequency modulation. In particular, digital technologies can guarantee:

- high and constant quality;
- ruggedness against noise and interference;
- spectrum efficiency and planning flexibility;
- reduction of the satellite power;
- flexibility of the digital multiplex for different service configurations;
- efficient and impairment-free encryption and scrambling for conditional access.

For a digital HDTV satellite emission system, the overall service quality depends on both the intrinsic performance of the picture coding algorithm and the service availability, determined by the margin against noise and interference allowed by RF channel performance. The optimization of the system then requires a trade-off in the bit-rate allocation between "source coding" and "channel coding" to achieve the highest picture quality and service continuity, while ensuring the best exploitation of the spectrum resources.

The present article gives the results of an investigation, including computer simulations and laboratory evaluations, into the RF performance of different modulation and channel coding systems, suitable for W-HDTV BSS in the 20-GHz range. Source coding is not a key issue in this study and a hybrid discrete cosine transform (DCT) is assumed as the basic bit-rate reduction method. Three advanced digital modulation and channel coding techniques have been considered and their performance has been compared in terms of power requirements, protection ratios, channel spacing and total number of available channels. These digital techniques are evaluated in the context of a possible "common frequency allocation" of 600 MHz bandwidth, in the range 21.4 to 22 GHz. This interesting approach would allow very efficient use of the spectrum by assigning the whole of the available bandwidth (on one or both polarizations) to all service areas.

2. Wide band HDTV service requirements

The basic requirements of a W-HDTV satellite broadcasting service are focused on the achievement of high picture quality and service availability. A high-definition television system is defined as "...a system designed to allow viewing at about three times picture height, such that the quality is virtually or nearly transparent to the quality of portrayal that would have been perceived in the original scene...". The service quality for the W-HDTV emission system should therefore preserve the maximum static definition potentially available from the studio standard. The maximum dynamic resolution may be reduced, but in a less systematic way, and to a lesser extent, compared to narrow RF-band systems such as HD-MAC or MUSE.

The *intrinsic picture quality* of a digital HDTV system depends on the performance of the source coding algorithm and on the transmission bit-rate. In general, the higher the bit-rate the lower the probability of perceptible artifacts in the picture due to the vision coding process. The objective is to deliver to the home a quality which, subjectively, is virtually transparent to the HDTV studio quality; this can be achieved by the hybrid DCT algorithm, with motion compensation, at 110-120 Mbit/s for the coding of the vision signal, although lower bit-rates can still provide adequate picture quality for most of programme material. With the HDTV source and display technology currently available, the picture quality achievable at 70 Mbit/s (including vision, sound, data and error correction redundancy) is generally very high for a large percentage of reproduced material, and it seems acceptable to most viewers. The results of recent EBU subjective evaluations [1] and experimental HDTV transmissions carried out by the RAI on the occasion of "Italia 90" [2] confirm this impression. In the present study it is therefore assumed that near-studio quality is achievable at a total bit-rate of 140 Mbit/s, but lower bit-rates such as 105 and 70 Mbit/s, which are still capable of providing high-quality HDTV, are also considered with a view to improving the overall RF system performance by allocating part of the bit-rate to channel coding for error protection, and/or to increase the total number of channels.

The *service quality* objective for conventional television systems in the 12 GHz band was set by the WARC'77 to achieve "good quality" for 99% of the worst month. The service quality for W-HDTV systems is expected to be even more demanding: a quality grade in the range from 4.5 to 5 in the CCIR 5-grade scale, referred to in the following as "High Quality" (HQ), is seen as a basic target to be achieved for at least 99% of the worst month within the service area. A second factor, of very considerable importance for operation at 20 to 22 GHz, is the *service outage time*, or "the percentage of time during which a service interruption occurs as a result, for example, of extreme rain attenuation". An ideal service continuity target would be 99.9% of the worst month; this is currently achievable by conventional television systems at 12 GHz. In terms of time, 1% of a month corresponds to 7 hours and 12 minutes, and 0.1% to 43 minutes. At 22 GHz an outage time of 0.1% of the worst month may not be achievable in regions affected by heavy rain fades such as the parts of Italy in climatic zone L, (see *Section* 5), even in the case of high power on the satellite; accordingly, a service availability of 99.6% (2 hours 52 minutes outage in the worst month) is proposed as a reasonable target.

Unlike analogue frequency-modulated television systems, which exhibit a gradual transition to outage, digital systems are normally characterized by a high basic quality which is fairly constant as long as the error rate remains below a threshold value which is set by the system design. However, when this threshold is exceeded the system performance deteriorates rapidly. Moreover, the effect of errors on the displayed picture depends on the picture coding algorithm and on the error-correction technique (FEC) adopted in the HDTV codec. If, for example, the codec includes a Reed-Solomon code RS(255,239) the system failure characteristic is very steep, with the threshold at a bit-error ratio (BER) of about 2.10^{-3} at the decoder input. In contrast, if the RS(255,239) code is used in the advanced channel coding schemes described in *Section 3.3*, this threshold behaviour is not a disadvantage because the carrier-to-noise ratio (C/N) at which the service outage occurs is so low (i.e. 3 to 4 dB) that the digital demodulator can barely recover the carrier and clock synchronization. Recent experiments on the performance of HDTV codecs based on hybrid DCT [1] shows that a BER of 10^{-8} to 10^{-10} is required to ensure high quality (HQ) pictures. A BER of about 10^{-10} after correction by the RS(255,239) code can be achieved with a BER of about 2.10^{-4} at the HDTV decoder input, assuming statistically independent errors.

From the above considerations the W-HDTV service quality can be expressed in terms of BER at the input of the decoder (before error correction by the RS code) as follows:

- high-quality pictures
  (HQ): $BER_{HQ} = 2.10^{-4}$
- service continuity
  (SC): $BER_{SC} = 2.10^{-3}$

The following targets are proposed for the W-HDTV system design:

- high-quality picture:
  99% of worst month
- service continuity:
  99.9% of worst month (if possible)
  99.6% of worst month (at least).

3. Modulation and channel coding

The main transmission requirements of a digital W-HDTV system by satellite designed to operate in the 22 GHz band are:

- ruggedness in the presence of noise: the system must ensure a sufficiently large C/N margin even when operating under severe propagation conditions;
- ruggedness against interference: the system must be able to operate with low protection ratios for efficient exploitation of the allocated bandwidth. This can be achieved by assigning all of the bandwidth to each service area on both polarizations (frequency re-use);
- high spectral efficiency (bit/(s.Hz)) and low spectrum-spreading;
- ruggedness against non-linear distortions (AM/AM; AM/PM) introduced by the satellite

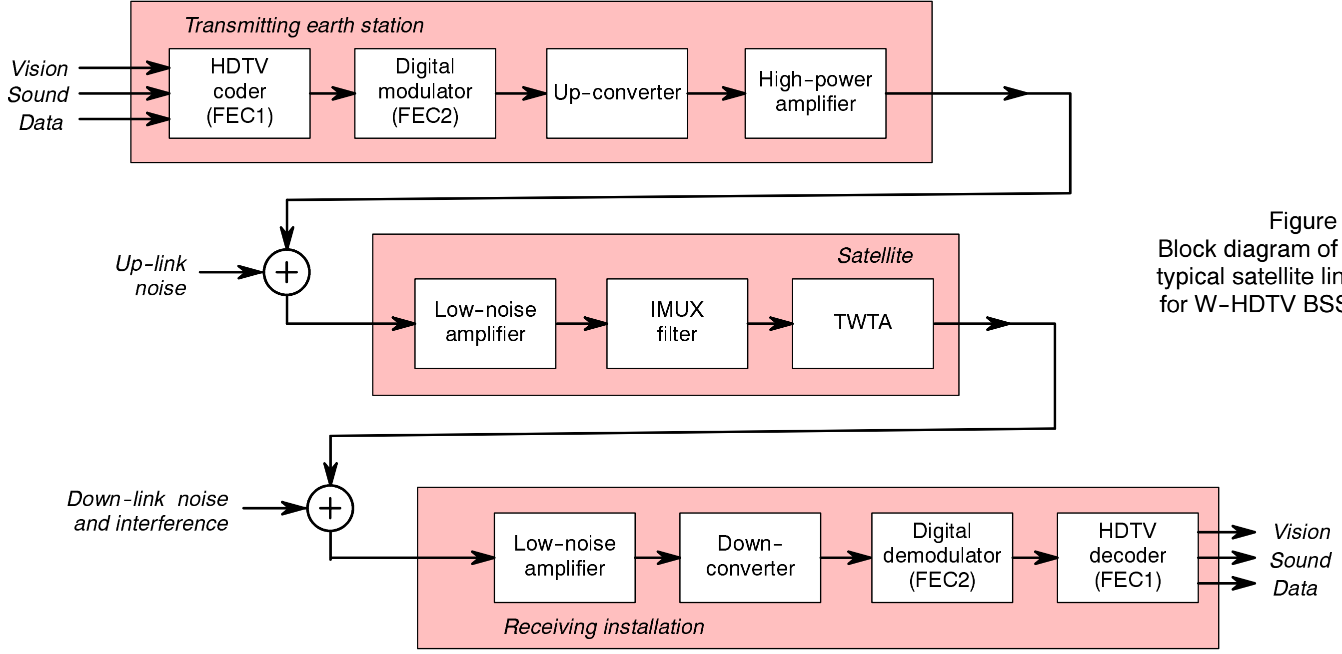

Figure 1
Block diagram of a typical satellite link for W-HDTV BSS.

travelling-wave tube power amplifier (TWTA).

3.1. The satellite channel

A typical satellite transmission chain includes the following blocks (*Fig. 1*):

- HDTV coder including RS(255,239) forward-error correction (FEC1);
- digital modulator incorporating FEC2;
- transmitting earth station (up-converter and high-power amplifier);
- satellite (low-noise amplifier, input multiplex filter, travelling-wave tube and output multiplex filter (LNA, IMUX, TWTA, OMUX, respectively);
- receiving installation (low-noise amplifier, down-converter);
- digital demodulator and FEC2 Viterbi decoder;
- HDTV decoder including the RS(255,239) decoder (FEC1).

The computer simulations presented here take into account a simplified transmission chain, including pseudo-random generator, channel coders and modulators, linear up-link station, satellite TWTA, ideal demodulator filters and carrier/clock recovery systems, and 3 to 4-bit soft decision Viterbi decoders. Only down-link noise and interference, originated on the same satellite by other channels and by other satellites (see *Section 4*), have been considered.

3.2. Digital modulations

Suitable methods of modulation are QPSK, offset-QPSK, 8-PSK and constant-envelope modulation systems such as minimum-shift keying (MSK). These digital techniques offer bandwidth efficiencies of 2 to 3 bit/(s.Hz) in the Nyquist bandwidth. Higher order, multi-level systems such as 16-PSK, MAMSK and 16QAM offer bandwidth efficiencies of about 4 bit/(s.Hz) but are very sensitive to non-linear distortions affecting the channel, and to noise and interference. The effects of the TWTA non-linearities on the curves of BER versus E_{bs}/N_o* for various degrees of TWTA output back-off (OBO) have been measured on QPSK, 8-PSK and 16QAM modems, using a hardware satellite simulator. The 16QAM modem has been tested with and without a TWTA linearizer. *Fig. 2* shows the values of E_{bs}/N_o, required for BER=10^{-5}, as a function of OBO.

QPSK can operate efficiently with the TWTA close to saturation (OBO=0 dB) with an E_{bs}/N_o of about 12 dB. 8-PSK is slightly more sensitive to TWTA non-linearities than QPSK: the optimum performance is achieved with OBO at about 0.2 to 0.5 dB and an E_{bs}/N_o ratio of 17.3 dB. 16QAM is

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* E_{bs} = energy per information bit available at TWTA saturation
= C/Ru, where C = TWTA power at saturation;
$N_o/2$ = noise power density.

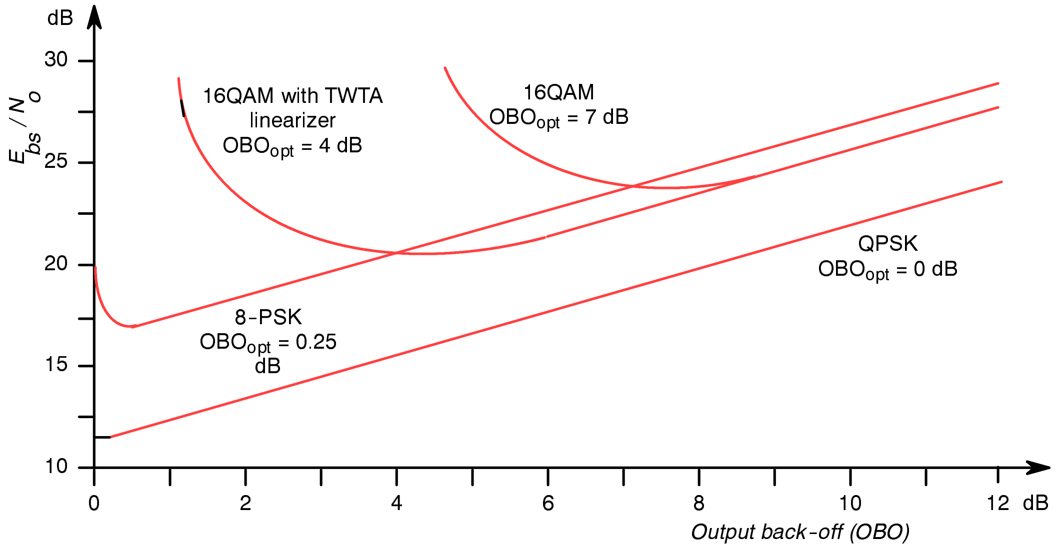

Figure 2
Influence of the satellite TWTA output back-off on the performance of QPSK, 8-PSK and 16QAM modulations. (curves for BER = 10^{-5})

very sensitive to non-linearities because of its inherent amplitude modulation: the optimum operating point corresponds to an OBO of 7 dB, with an E_{bs}/N_o ratio of 24 dB. The use of a TWTA linearizer allows operation with an OBO of about 4 dB and an E_{bs}/N_o ratio of 20.5 dB. QPSK is well-established for its ruggedness against noise and interference and for the simplicity and low cost of the demodulator. However, a high-quality HDTV service demands a low bit-error ratio and neither QPSK nor 8-PSK can be used without powerful error correction: otherwise an excessive satellite power would be required.

3.3. *Advanced channel coding techniques*

Modern trends in satellite digital communications favour the use of "concatenated schemes" for error correction based on block codes and convolutional codes, associated with "soft decision" Viterbi decoding. This sophisticated decoding algorithm, already used in various applications, offers large power gain, and this is a fundamental requirement for W-HDTV broadcasting satellites at 22 GHz.

Three advanced modulation and channel coding systems have been investigated [3, 4] (see *Fig. 3*):

System A1:

QPSK with rate 1/2 convolutional code (FEC2) concatenated with a RS(255,239) block code associated with the source (FEC1).

System A2:

QPSK with rate 3/4 convolutional code (FEC2) concatenated with a RS(255,239) block code associated with the source (FEC1).

System B:

Trellis-coded (rate 2/3) 8-PSK (Ungerböck modulation) in combination with a RS(255,239) block code associated with the source (FEC1).

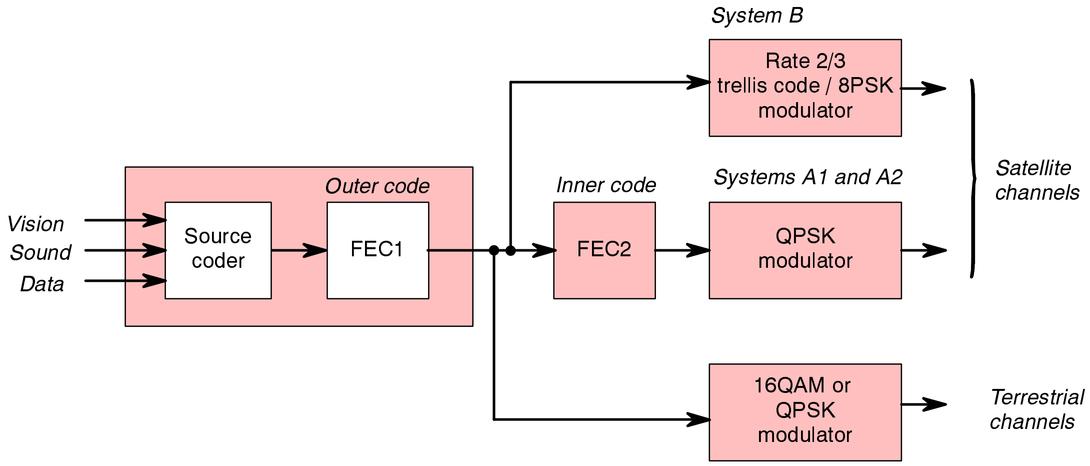

Figure 3
Channel coding and modulation techniques for W-HDTV.

All three systems make use of soft-decision Viterbi decoding in the receiver.

In systems A1 and A2, the function of the inner code (FEC2) is completely independent of the modulation and the code redundancy reduces the spectral efficiency of the system with respect to uncoded QPSK modulation. The rate 1/2 convolutional code has a constraint length of 7. The rate 3/4 convolutional code is obtained by "puncturing" the rate 1/2 code. In the system B approach, modulation and coding can be considered as a unique process (the redundancy is inherent to the signal-space constellation) and the spectral efficiency is equal to that of uncoded QPSK. The rate 2/3 trellis code has 8 states [5]. In order to achieve the optimum coding gain, the soft-decision Viterbi decoders operate on 3-bit symbols for QPSK and on 4-bit symbols for 8-PSK.

3.4. System optimisation

In the concatenated coding schemes adopted in systems A1, A2 and B, the errors at the output of the Viterbi decoders are not statistically independent (as is the case in uncoded transmission over AWGN channels) but are instead grouped in bursts. The occurrence of error bursts longer than the error-correction capability of the RS(255,239) code, e.g. 57 bits, has a destructive effect on the decoded HDTV pictures. The performance of the RS(255,239) code is heavily dependent on the statistical distribution of burst lengths and this is directly related to the average bit-error ratio. The burst-error correcting capability can be improved by using an interleaving technique; this effectively "subdivides" the long error bursts into shorter ones, thus avoiding overloading of the RS code*.

The interleaving depth *I* must be carefully optimized according to the burst length distribution. The statistical distributions of error bursts after Viterbi decoding of convolutional codes, with rates 1/2 and 3/4, and trellis-coded 8-PSK (rate 2/3) have been evaluated by computer simulations using the Montecarlo method. *Fig. 4* shows, for the three cases, the burst-length cumulative distribution function (CDF), i.e. the probability of error bursts shorter than *m* bits, at various values of BER.

At BER=1.10^{-3}, 95% of the bursts have the following maximum length:

- system A1: 22 bits
- system A2: 42 bits
- system B: 29 bits.

The rate 1/2 decoder of system A1 generates the shortest error bursts. The puncturing process in system A2 significantly increases the burst length. Although most error bursts are within the correction capability of the RS code, the use of a suitable interleaving is necessary to avoid performance degradations.

The VLSI Viterbi decoders currently available on the market operate at a maximum useful bit-rate of 20-30 Mbit/s. As a result, practical hardware implementations require two or more Viterbi VLSI chips working in parallel to process the high bit-rate of the HDTV signal. In this situation the burst lengths increase, because a burst at the output of one Viterbi decoder is mixed with bits from the other Viterbi decoders; the performance of the concatenated RS code is therefore impaired. To avoid this degradation an interleaving depth *I* of at least 4 is required or, alternatively, the concatenated decoders (Viterbi and RS), need to be synchronized at byte level.

Modulation/ coding system	Interleaving depth (I)	Coding gain at BER = 10^{-8} (dB)	E_b/N_o at BER = 2.10^{-4} before RS correction	Relative RF channel bandwidth (%)
QPSK + RS	-	-	8.8	94
System A1	2	4.4	4.1	
	4	4.7		47
System A2	2	3.3	5.2	
	4	3.7		70
System B	2	2.0	6.7	
	4	2.4		94

Table 1
Performance of modulation and channel coding systems.

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* In the interleaving process, the data stream at the output of the Viterbi decoder is written row-by-row into a matrix memory (*N* rows, *I* columns), and read column-by-column to feed the RS decoder.

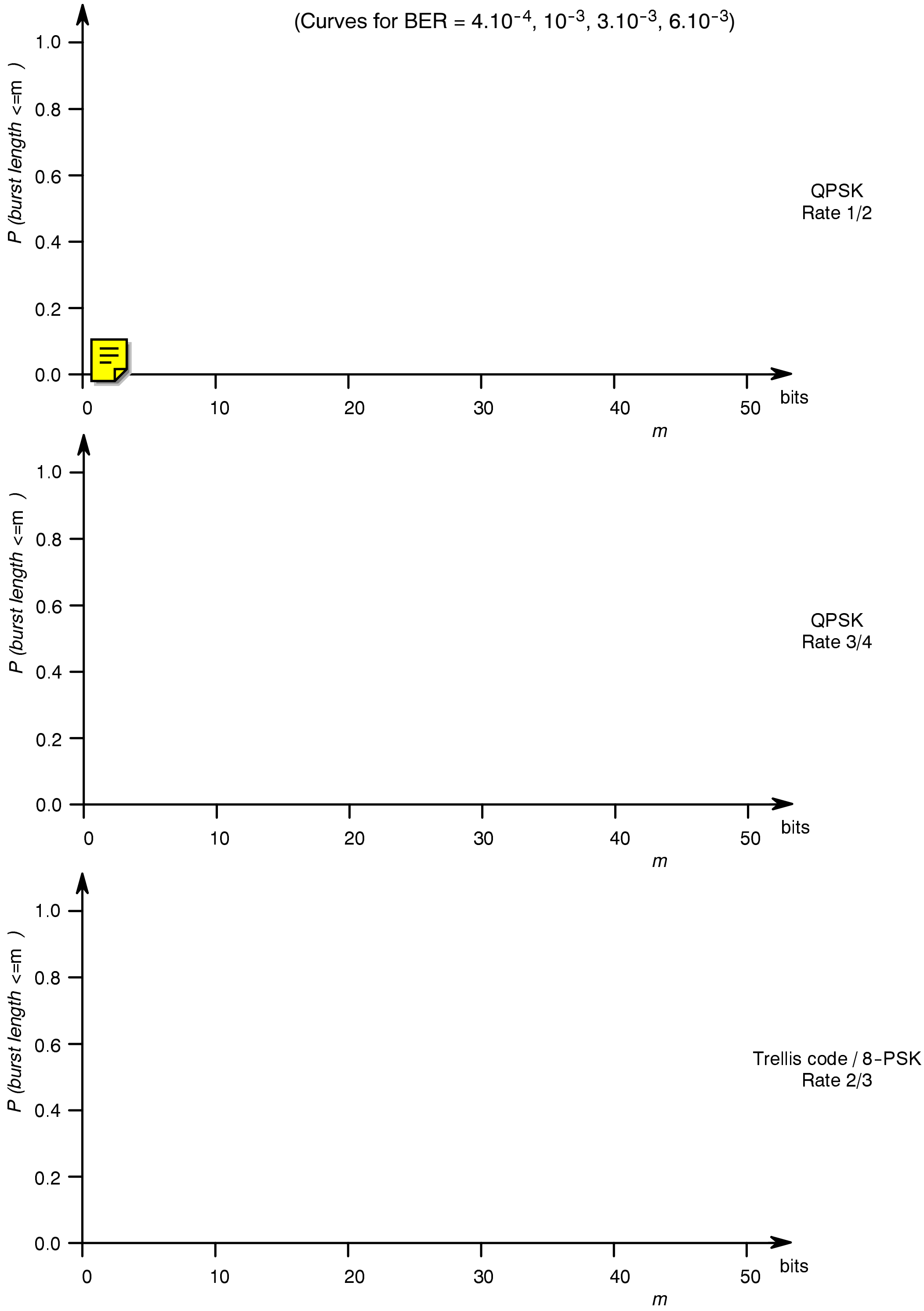

Figure 4
Cumulative distribution function of error burst lengths, after Viterbi decoding.

Fig. 5 shows the E_b/N_o ratio as a function of the BER performance of systems A1, A2 and B, through the satellite channel and without interference. The improvement achieved by increasing the interleaving depth on the RS code is shown. For all three systems (A1, A2 and B), with BER=2.10^{-4} at the input to the HDTV decoder, the use of interleaving depths of 2 and 4 is sufficient to achieve a residual BER on the HDTV pictures of about 10^{-8} and 10^{-10}, respectively. With interleaving I=4 the coding gain is approximately 0.3-0.4 dB higher than with I=2 (BER=10^{-8}).

Table 1 compares the performance of the systems, obtained by computer simulations including the satellite channel with a saturated TWTA and Gaus-

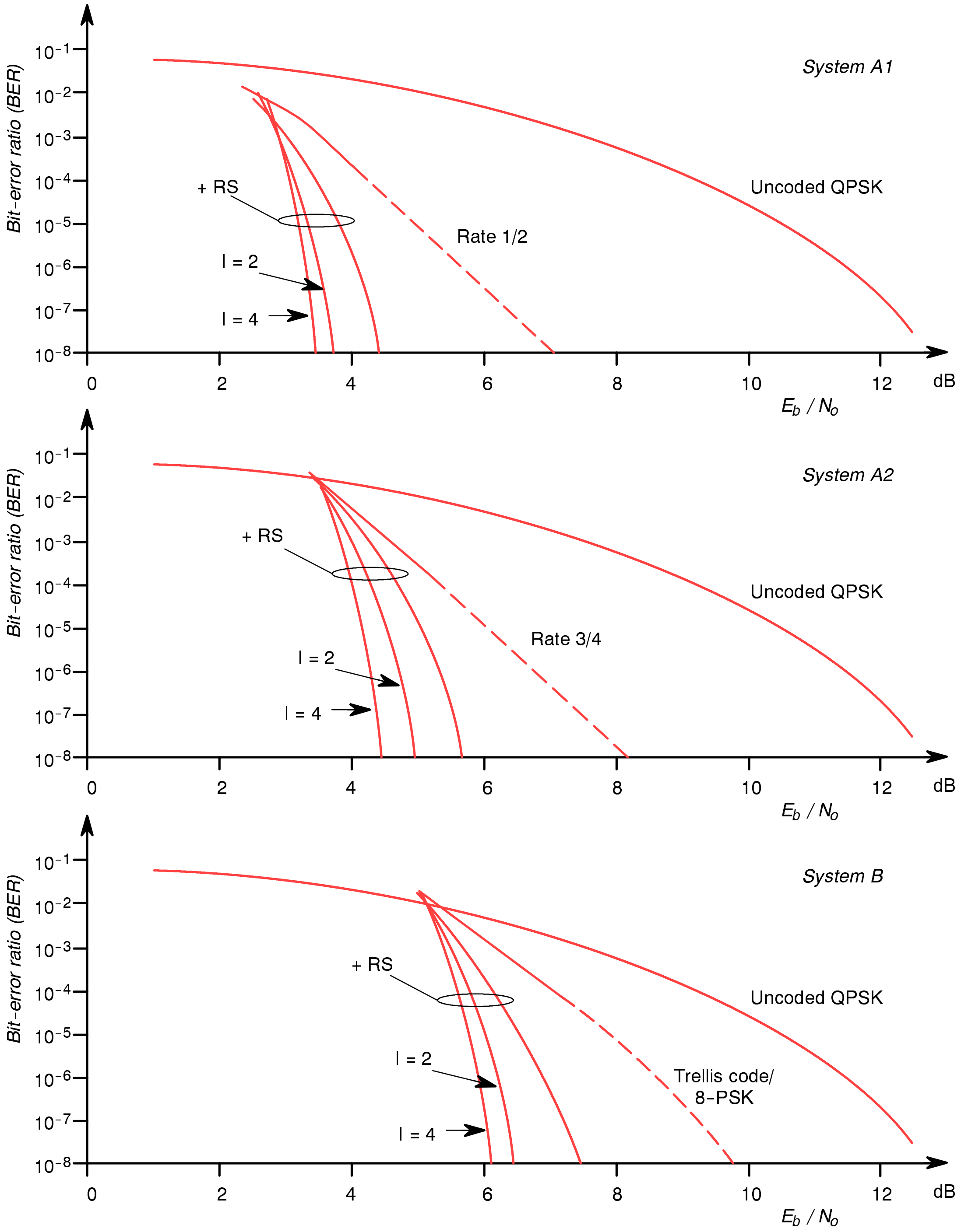

Figure 5
Bit-error ratio as a function of the E_b/N_o performance of systems A1, A2 and B, in a simulated satellite channel.

sian noise but without interference; it is assumed that the bit-rate at the output of the HDTV coder, including the RS(255,239) code (FEC1), is the same for all three coding schemes.

The systems are compared in terms of:

- coding gain with interleaving I=2 and 4 at BER=10^{-8} with respect to QPSK + RS(255,239);
- E_b/N_o ratio required for high-quality HDTV pictures (BER = 2.10^{-4} before RS error correction);
- relative RF channel bandwidth with respect to un-coded QPSK.

It may be noted that systems A1 and B present complementary characteristics: the first one gives the highest coding gain, the second one the highest spectral efficiency.

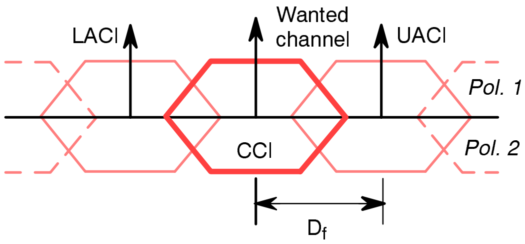

Figure 6
Channelling scheme for digital HDTV transmission by satellite.

LACI: lower adjacent-channel interferer
UACI: upper adjacent-channel interferer
CCI: co-channel interferer
D_f channel spacing

4. System performance in a complete interference environment

4.1. Channel configuration and interference sources

The three channel coding systems A1, A2 and B have been compared over a satellite channel, in the presence of interference, in terms of the basic RF parameters: C/N ratio required for high-quality pictures (HQ) and for service continuity (SC), protection ratios required to safeguard the wanted signal against interference, channel spacing (D_f) and number of channels (N) that can be accommodated in 600 MHz.

Three useful bit-rates (Ru) at the HDTV coder output (including video, audio, data and FEC1) have been considered: 140, 105, and 70 Mbit/s.

This permits an investigation of different trade-offs between intrinsic picture quality (increasing with Ru), ruggedness against noise and interferences (increasing with FEC2 redundancy) and number of HDTV channels which can be allocated within the 600 MHz bandwidth. In the following examination each system will be identified by its modulation and coding family (A1, A2 and B) and by the value of Ru (e.g. “A2-105” is the rate 3/4 convolutional coded QPSK at Ru=105 Mbit/s).

The channel matrix adopted in this study is shown in *Fig. 6*. It is composed of an array of channels of equal widths, spaced by D_f; every channel is used on each of the two polarizations [4]. In order to simplify the analysis, no guard-band has been considered at the edges of the 600 MHz band to protect other services.

It is assumed that the entire 600 MHz bandwidth is assigned to each service area, using either a single polarization or both polarizations (frequency re-use); this planning approach is called a “common frequency plan” [6]. All channels covering a service area are transmitted from the same satellite and have the same power level. In this configuration the interference contributions can be classified as follows:

Type A: The upper and lower co-polar adjacent channels (UACI and LACI) from the same satellite as the wanted signal.

The protection ratio is defined as the ratio between the power of the wanted carrier and the total power of the un-modulated interfering carriers. The carrier power of each ACI is equal to that of the

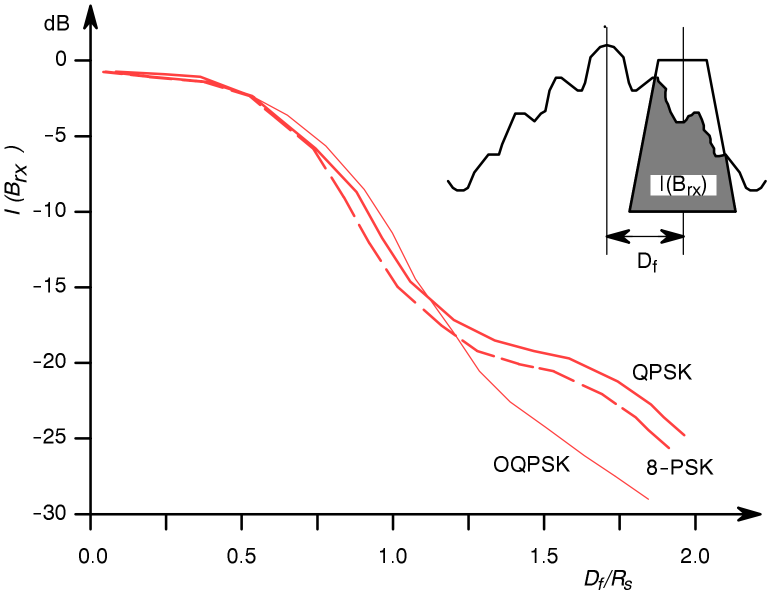

Figure 7
Interfering power of digital signals at the same symbol rate R_s measured in the receiving filter of an adjacent channel, as a function of the normalized channel spacing D_f/R_s.

Roll-off : 0.5
QPSK, OQPSK : TWTA OBO = 0 dB
8-PSK : TWTA OBO = 0.3 dB

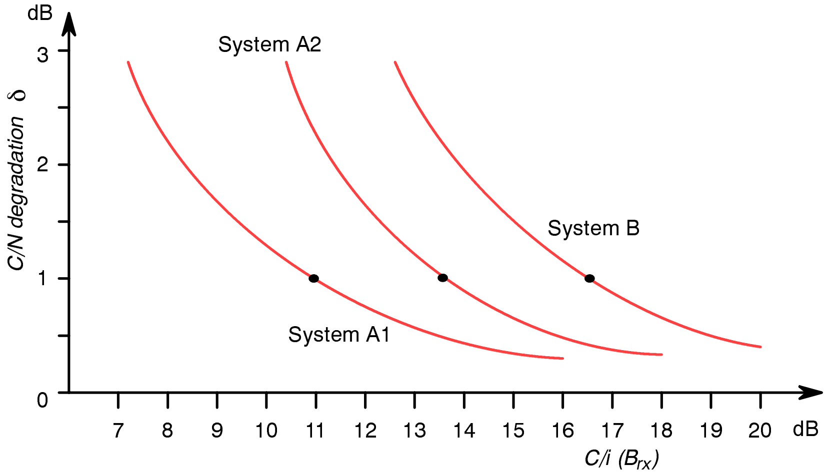

Figure 8
C/N degradation due to interference for systems A1, A2 and B, after Viterbi decoding. (BER = 2.10^{-4})

wanted carrier. The ACI protection ratio is therefore: PR(LACI)=PR(UACI)=0 dB.

Type B: The sum of the signals serving other service areas (and the same service area on the opposite polarization, in the case of frequency re-use).

PR(CCI) is the equivalent co-channel protection ratio corresponding to a system C/N degradation δ dB at BER=2.10^{-4}. This degradation δ also includes the contribution of Type A interferences. The C/N degradation δ depends on the total interfering power in the receiving filter.

Although each contribution relative to a service area is composed by *N* channels at the same power level, the most important is the co-channel (CCI) because the ACIs are efficiently filtered by the receiver. The sum of the co-channel interferences is indicated as the "equivalent" co-channel contribution.

The non-linearity of the satellite TWTA, operating close to saturation, regenerates the spectrum sidelobes and the adjacent channels interfere partially with each other. *Fig. 7* shows the interfering power of QPSK, Offset-QPSK and 8-PSK measured in the bandwith B_{rx} of the receiving filter of an adjacent channel, for different values of the normalized channel spacing D_f/R_s. D_f is the effective channel spacing and R_s is the symbol rate of the digital modem*.

In the range of practical D_f/R_s values, i.e. from 1.1 to 1.5, there is only a slight advantage, in terms of interfering power reduction, if Offset-QPSK is adopted instead of QPSK. Accordingly, for the purpose of the study, QPSK has been chosen for system A1 and A2, in view of its superior C/N performance and implementation simplicity. *Fig. 8* shows the C/N degradation, for BER=2.10^{-4} after

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* R_s=Ru.M, where M=1 for system A1, M=2/3 for system A2 and M=1/2 for system B.

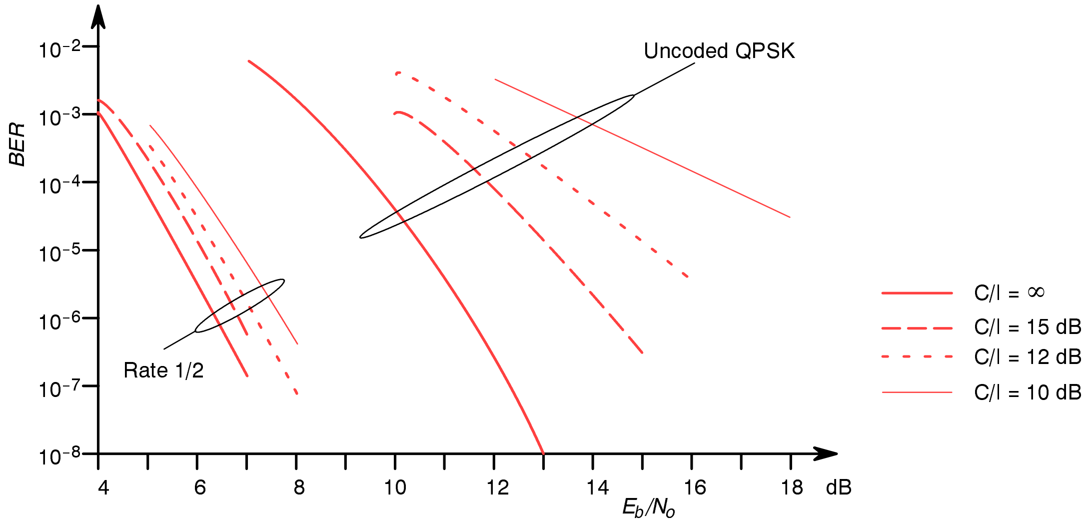

Figure 9
BER performance of a digital modem of the A1 family in the presence of co-channel interference.

Viterbi decoding, versus the carrier-to-interference ratio (C/I). The interfering power (I) has been measured in the bandwidth (B_{rx}) of the receiving filter. System A1 gives the greatest ruggedness against interference. For a C/N degradation of 1 dB it can operate with a co-channel C/I ratio of 11 dB. For the same C/N degradation, systems A2 and B require higher C/I values: 13.8 dB and 16.7 dB, respectively.

The error performance of system A1 in the presence of noise and interference has been assessed by laboratory measurements on a prototype QPSK modem with a convolutional code (rate 1/2, associated with Viterbi decoding), operating at a useful bit-rate Ru=17 MBit/s [7]. The tests were carried-out with a modem in back-to-back IF configuration; noise and co-channel interference were added at the demodulator input. The results are shown in *Fig. 9*. The system is able to cope with co-channel carrier-to-interference ratios as low as 10 dB with an E_b/N_o degradation of about 1 dB at BER=2.10^{-4}. These results are in good agreement with those obtained in computer simulations.

4.2. Evaluation of basic planning parameters

Table 2 gives the performance of the three systems in a complete interference environment, in terms of:

- Ru = bit-rate at the output of the HDTV coder (including video/sound/data and RS(255,239) redundancy);
- C/N ratios required in 100 MHz for high quality pictures (HQ) and for service continuity (SC), corresponding to BER = 2.10^{-4} and BER = 2.10^{-3}, after Viterbi decoding, respectively;
- co-channel protection ratios PR(CCI), for a C/N degradation δ=1 dB at BER=2.10^{-4} [*];
- channel frequency spacing (D_f);
- number of available channels (*N*) in 600 MHz bandwidth on one polarization.

The following assumptions have been made:

- raised-cosine modem filters, roll-off α=0.5;
- TWTA OBO=0 dB for QPSK, OBO=0.3 dB for TC-8PSK; wide-band OMUX filter;
- ideal carrier and clock recovery;
- 2 dB implementation margin;
- total bandwidth 600 MHz, no guard-band;
- no up-link noise or interference;
- D_f/R_s= normalized channel spacing=1.428.

Because of the fixed value D_f/R_s, the CCI protection ratio, for each system, is independent of the useful bit-rate.

The values given in *Table 2* are the main system parameters required for planning purposes. The following preliminary observations may be made:

System A1 offers the lowest spectral efficiency (1 bit/(s.Hz) in the Nyquist bandwidth), but is the

Table 2
System performance through a simulated satellite channel.

Ru	**System**	**D_f**	**Channels in 600 MHz**	**PR(CCI)**	**C/N ratio required in 100 MHz (2dB implementation margin)**	
Mbit/s		**MHz**	***N***	**dB**	**HQ - dB**	**SC - dB**
140	QPSK + RS	100	6	20.0	14.1	11.6
70	A1	100	6	11.1	5.6	4.6
	A2	66.7	9	15.3	6.6	5.7
	B	50	12	20.2	8.2	7.2
105	A1	150	4	11.1	7.4	6.4
	A2	100	6	15.3	8.4	7.5
	B	75	8	20.2	10.0	9.0
140	A1	200	3	11.1	8.6	7.6
	A2	133	4	15.3	9.7	8.8
	B	100	6	20.2	11.2	10.2

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[*] For uncoded QPSK a degradation of 1.8 dB was accepted in order to operate at PR(CCI)=20 dB.

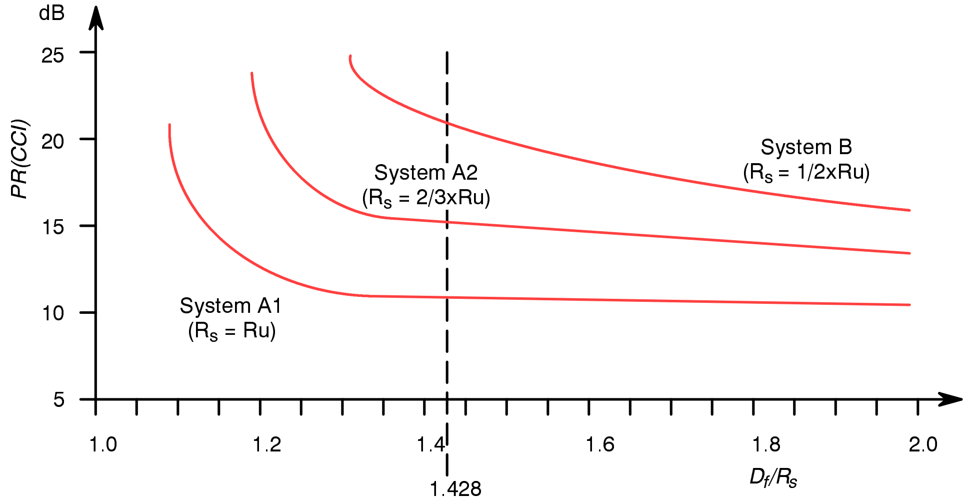

Figure 10
Co-channel protection ratio PR(CCI) of systems A1, A2 and B, as a function of the normalized channel spacing, for a C/N degradation of 1 dB and BER = 2.10^{-4}.

most rugged in the presence of noise and interference; it requires the lowest C/N ratio and a PR(CCI) of about 11 dB.

System B offers the highest spectral efficiency (2 bit/(s.Hz) in the Nyquist bandwidth) but requires an increase of 2.6 dB in C/N ratio with respect to system A1 and a PR(CCI) of about 20 dB.

System A2 represents a compromise between the other two systems: it has a spectral efficiency of 1.5 bit/(s.Hz) and requires a C/N ratio which is 1 dB higher than system A1 and a PR(CCI) of about 15 dB.

If the useful bit-rate of Ru=140 Mbit/s is chosen to ensure transparency to studio quality, system A1 would allow three channels to be accommodated in the 600-MHz bandwidth (on each of the two polarizations); system A2 allows four channels and system B six channels. If the bit-rate is reduced to Ru=70 Mbit/s, which still ensures high picture quality, the power can be reduced by 3 dB and the maximum number of channels is doubled. This would permit the operation of six channels with system A1, nine with system A2 and twelve with system B, on each polarization. If both polarizations are assigned to the same service area, system A2 appears as a very attractive solution, because the number of channels per service area is sufficiently high (18) and a good service availability can be achieved (see *Section 5*).

In *Table 2* the normalized channel spacing D_f/R_S is set at 1.43. The ruggedness against interference of systems A1 and A2 can be exploited to reduce the channel spacing; by this means one or two more channels could be accommodated, or suitable guard bands could be provided to protect adjacent services from out-of-band spurious emissions. The optimisation of D_f/R_S can be carried out easily with the aid of the curves of *Fig. 10*, once the values of PR(CCI) obtained from planning exercises are known.

For example, assuming that the plan allows operation with an equivalent co-channel carrier to interference ratio C/I which is greater than 15 dB at all the test points, the normalized channel spacing of system A1 could be reduced from 1.43 to 1.13 with a C/N degradation $\delta = 1$ dB. Under these conditions system A1-70 could operate efficiently with a channel spacing of 79.1 MHz, making available a total of 14 channels (2 x 7 using both polarizations) and allowing, in addition, a guard-band of about 46 MHz.

5. An example of 22-GHz W-HDTV BSS (Italy)

In order to assess the feasibility of W-HDTV BSS at 22 GHz using the channel coding techniques examined above, link budget evaluations have been carried out for the case of coverage of Italy. Most of the territory is in climatic zone K, although zone L, which is representative of the most unfavourable propagation conditions in Europe, is also considered (relevant for the north-west of Italy).

The link budgets have been evaluated for the following conditions:

- satellite TWTA power: 300 W
- receiver noise figure: 2.5 dB, coupling losses 1 dB
- down-link frequency: 22 GHz;
- satellite position: 19°W
- satellite losses (waveguide, OMUX filter): 1.5 dB
- satellite maximum e.i.r.p.: 67.3 dBW

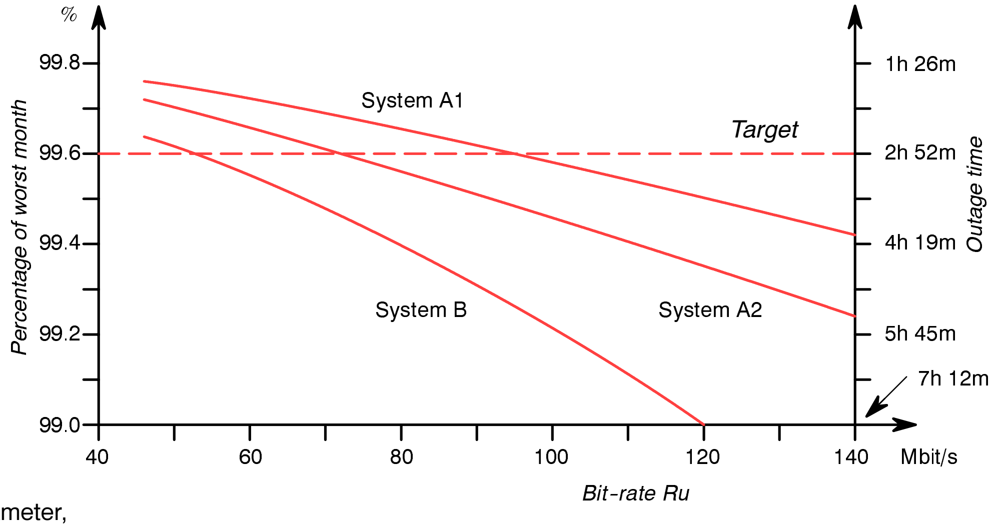

Figure 11
Service availability in climatic zone K in Italy, for systems A1, A2 and B, as a function of the useful bit-rate Ru.

Satellite TWTA: 300 W
Receiving antenna: 90 cm diameter, G/T = 16.7 dB/K

- test point: on the -3 dB service area contour
- receiver G/T: 16.7 dB/K (dish: 90 cm, efficiency 65%)
- up-link noise contribution: 0.5 dB.

The values of rain attenuation and gaseous absorption have been computed as a function of the percentage of time of the worst month using the method of CCIR Report 564-3 Mod F. In the regions in climatic zone L the figures for rain attenuation and gaseous absorption at 22 GHz are: 10 dB (99% of worst month), 14.5 dB (99.6%) and 26.5 dB (99.9%). The other parts of Italy, in climatic zone K, are less affected by these severe rain attenuations. However the corresponding figures are still high: 8.5 dB (99% of worst month), 12.1 dB (99.6%) and 21.2 dB (99.9%). In any case, owing to the limited knowledge of the rain attenuation statistics in this frequency range, the results obtained in this example should be used only for qualitative comparisons of the performance of the various systems. Clear-sky C/N margins have been evaluated for the three systems (A1, A2 and B) as a function of the useful bit-rate Ru, for high quality pictures (BER=2.10^{-4}) and for service continuity (BER=2.10^{-3}). The corresponding percentages of time in the worst month have then been determined.

The increase of rain attenuation between 99% and 99.6% of the worst month is much higher then the difference between C/N_{HQ} for unimpaired pictures and C/N_{SC} for service continuity (about 1 dB). The most severe target is therefore the 99.6% service continuity.

In zone K, at the highest bit-rate of 140 Mbit/s, systems A1 and A2 satisfy the target of high picture quality for 99% of the worst month (BER = 2.10^{-4}), with 90-cm dishes. Using the same antenna, system B could operate at about 100 Mbit/s. Using a receiving antenna of 75 cm, system A1 could operate at 120 Mbit/s, system A2 at 95 Mbit/s and system B at 70 Mbit/s. In zone L, with a 90-cm dish, the 99% target is achieved by systems A1-140, A2-105 and B-70.

Fig. 11 gives, for climatic zone K and with a 90-cm receiving antenna, the percentage of the worst month for which service continuity is guaranteed, as a function of Ru. The service outage times are also indicated. The service continuity target of 99.6% of the worst month (BER = 2.10^{-3}) is achieved by system A1 at about 95 Mbit/s, and by system A2 at 70 Mbit/s; this target is only approached by system B-70 (about 99.5%). Under the severe propagation conditions of zone L, the adoption of reduced bit-rates (e.g. 70 Mbit/s) or larger antenna diameters would be necessary.

6. Influence of PR(CCI) on spectrum exploitation

The three systems A1, A2 and B have been evaluated for operation in the channel configuration of *Fig. 6,* and with a C/N degradation of $\delta=1$ dB.

In a planning exercise, protection from interference can be achieved by frequency separation of the channels, by cross-polar discrimination, by geographical separation of the service areas and by orbital separation of the satellites. Systems that can operate with low values of PR(CCI) and PR(ACI) allow more efficient use to be made of the available spectrum. The maximum efficiency is obtained when it is possible to assign the overall available bandwidth (on one or both polarizations) to the service areas: this type of plan is known as a "common frequency plan" [6]. This approach was not possible at the WARC'77 because of the use of analogue FM systems requiring a PR(CCI) of 31 dB and PR(ACI) of 15 dB, with a channel spacing of 19.18 MHz.

An important feature of the common frequency plan is that the choice of modulation parameters, bit-rates and channel spacings can be left to the user; the only restriction concerns the maximum permitted power density needed in order to protect the other services from interference. Service areas affected by severe propagation conditions can therefore adopt very rugged modulation and coding schemes to protect themselves against noise and interference, at the expense of a reduction of the useful bit-rate (Ru) or of the number of available channels. For example, assuming that QPSK modulation is used with a fixed symbol rate, the use of punctured convolutional codes would allow the code rate to be changed easily (e.g. 1/2, 2/3, 3/4 and 7/8) according to the service area, without hardware modifications in the QPSK demodulator and Viterbi decoder.

Planning exercises have been carried out [8] in order to evaluate the number of channels that can be obtained per national service area in Europe and North Africa. The results indicate that a common frequency plan which assigns all the bandwidth (e.g. 600 MHz) to all the service areas, but using only one of the two polarizations, is feasible with a co-channel protection ratio PR(CCI) of 20 dB (assuming 3° satellite spacing and the WARC'77 antenna radiation pattern). The three systems A1, A2 and B can therefore operate in such a planning scenario; the number of channels available, N, is given in *Table 2*.

If the satellite spacing is reduced to 2°, and assuming the adoption of systems able to operate with PR(CCI) of only 15 dB, frequency re-use in the same service area becomes feasible, doubling the total number of channels per service area. Under these conditions systems A1 and A2 suffer from a C/N degradation d of about 0.4 and 1.1 dB, respectively. A total of 12 and 18 channels would be available with system A1-70 and system A2-70, respectively. System B could operate with frequency re-use, allowing 24 channels at Ru=70 Mbit/s, at the expense of a large C/N degradation (about 2 dB), which can be overcome by increasing the satellite power.

7. Conclusions

Among the objectives of the WARC'92 Conference in Spain, the allocation of a suitable frequency band around 20 GHz for wide-RF band HDTV satellite emission systems, with near studio quality, is of primary importance. To assess the feasibility of a fully-digital solution, potentially open to the expected technology evolution of the next century, three advanced channel coding and modulation systems have been identified and evaluated by computer simulations and laboratory tests (at scaled bit-rates) using a hardware satellite simulator:

- System A1: QPSK with rate 1/2 convolutional code;
- System A2: QPSK with rate 3/4 convolutional code;
- System B : rate 2/3 trellis-coded 8-PSK.

These systems make use of soft-decision Viterbi decoding in the receiver, and include a Reed-Solomon (255,239) concatenated block code associated with the HDTV coder.

The main objective of the study was to compare the RF system performance at different bit-rates (Ru=70, 105 and 140 Mbit/s, including video/audio/data information and 6% FEC redundancy), when working through a satellite channel in a complete interference environment, in terms of:

- number of channels available in a bandwidth of 600 MHz (21.4 to 22 GHz);
- service quality, in terms of percentage of time (in the worst month) for which high-quality pictures are available and service continuity is assured.

With current hybrid DCT bit-rate compression algorithms, near-studio quality HDTV is achievable at 140 Mbit/s. The adoption of reduced bit-rates, such as 70 and 105 Mbit/s, still allows high-quality HDTV, and assures significant improvements in the RF system performance; this could be a predominant factor in regions affected by severe propagation conditions, such as climatic zone L in northern Italy.

The following conclusions can be drawn:

- All systems, A1, A2 and B, have proved suitable for operation in a "common frequency plan", which allocates the whole 600 MHz bandwidth to each service area, on one or both polarizations (i.e. with frequency re-use). This approach allows a certain degree of flexibility in the final choice of the system and of the bit-rate, according to the propagation conditions and the service requirements. The final choice is then a trade-off between the required HDTV picture quality, the number of channels and the service availability.

- In countries where the satellite e.i.r.p. is not the limiting design parameter (low rain attenuation, small foot-print) system B, with frequency re-use, represents the optimum solution in terms of the number of channels available (i.e. 12, 16 and 24 at bit-rates of 140, 105 and 70 Mbit/s respectively).
- In countries affected by severe propagation conditions (e.g. high rain attenuation and low cross-polar decoupling) systems A1 and A2 are particularly suitable on account of their ruggedness in the presence of noise and interference. Moreover, the use of low bit-rates (e.g. 70 Mbit/s) allows a further improvement of the RF system performance.

As an example, the performance of the three systems at 22 GHz has been evaluated under the severe propagation conditions of Italy (climatic zones K and L), assuming a satellite TWTA power of 300 W. The results have proved the possibility of conveying unimpaired HDTV pictures to viewers for 99% of the worst month, using 90-cm receiving antennas:

- near-studio quality, at 140 Mbit/s, can be achieved in climatic zone K by systems A1 and A2, and in zone L by system A1;
- high-quality HDTV is feasible in zone K with system B-105, and in zone L with systems A2-105 and B-70.

Using a 75-cm receiving antenna, system A1 can operate at 120 Mbit/s for 99% of the worst month, system A2 at 95 bit/s and system B at 70 Mbit/s.

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In order to satisfy the target of service continuity for 99.6% of the worst month, particularly under the severe propagation conditions of zone L, a reduction of the bit-rate or an increase of the antenna diameter would be necessary. For example, system A1-70 could operate satisfactorily with a 100-cm dish in climatic zone L for 99.6% of the worst month, making available a total of 12 channels, using both polarizations.

The results of this investigation prove the feasibility of W-HDTV BSS, at frequencies around 20 GHz, using advanced modulation and channel coding techniques which are already mature for practical implementation. These techniques, based on concatenated error correction strategies and soft-decision Viterbi decoding, allow the broadcasters to exploit the inherent flexibility of the common frequency approach by offering a variety of solutions for W-HDTV broadcast satellite services, suitable for a variety of service requirements and propagation conditions, and able to cope with the technology of future satellites in the 20-GHz range.

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8-hours/day Hi-Vision

Following over two years of daily one-hour experimental satellite broadcasts of Hi-Vision, the Japanese Hi-Vision Promotion Association began test broadcasts for eight hours each day, beginning on 25 November 1991. The broadcasts are carried in a channel on the BS-3b satellite reserved exclusively for Hi-Vision.

The purpose of the expanded test programme is to increase awareness of Hi-Vision and the Association hopes to contribute, in this way, to the enhancement of Japanese culture and the living standard of the people. The Association represents companies and organizations from various fields, including the Japanese national broadcasting organization NHK, JSB (Japan Satellite Broadcasting) and commercial broadcasters in Tokyo, Osaka and Nagoya. NHK joined the Association on the understanding that the broadcaster's efforts to promote Hi-Vision during the earlier experiments would be fully appreciated, and that NHK would assume the leading rôle in the new Association.

NHK