Digital multi–programme TV/HDTV by satellite

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The progress of digital technology since the WARC'77 is considered and the perspectives of future applications via satellite channels are identified. Among these, digital multi–programme television systems, with different quality levels (EDTV, SDTV) and possible evolution to HDTV, are evaluated in terms of picture quality and service availability on the satellite channels of the BSS bands (12 GHz and 22 GHz) and of the FSS band (11 GHz) in Europe. A usable channel capacity of 45 Mbit/s is assumed, as well as the adoption of advanced channel coding techniques with QPSK and 8PSK modulations. For high and medium–power satellites, in operation or planned, the receiving antenna diameters required for correct reception are reported. High–level modulations (16QAM, 32QAM, 64QAM) are considered for distribution of the satellite signal in cable networks.

1. Introduction

The significant progress of digital techniques in production, transmission and emission of radio and television programmes is rapidly changing the established concepts of broadcasting.

The latest developments in VLSI (very–large scale integration) technology have significantly contributed to the rapid emergence of digital image/video compression techniques in broadcast and information–oriented applications; optical fibre technology allows broadband end–to–end connectivity at very high bit–rates including digital video capabilities; even the narrow–band terrestrial broadcast channels in the VHF/UHF bands (6–7 MHz and 8 MHz) are under investigation, in the USA [1] and in Europe [2], for the future introduction of digital television services.

The interest for digital television in broadcasting and multimedia communications is a clear example of the current evolution from the analogue to the digital world.

The satellite channels, either in the BSS bands (broadcast satellite service) at 12 GHz or in the FSS bands (fixed satellite service), offer an important opportunity for a short time–scale introduction of digital multi–programme television services, with possible evolution to high–definition television (HDTV).

In a longer term perspective, the new frequency band (21.4 to 22 GHz) allocated by the WARC'92 to wide RF–band HDTV (W–HDTV) services in

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Regions 1 and 3 will also offer important opportunities for new services.

2. Technology trends and the evolution of satellite television

Satellite television is developing rapidly in Europe in response to the emergence of new technologies and the creation of a favourable commercial environment through the deregulation of the communications sector. The success of satellite broadcasting depends on the programmes provided and, increasingly, on the way programme–providers can offer an attractive package for the various audiences. The set of parameters characterising the satellite are then important strategic factors contributing towards penetration of a dedicated market. Parameters to be considered are: orbital position, type of polarization (circular or linear), frequency band, satellite power, coverage, availability of backup capacity. Equally important are: technical quality and number of programmes delivered to the users, availability of reliable transmission systems and low–cost receivers.

2.1. The need for modernisation of the WARC'77 Plan

The WARC'77 Plan was established for the use of BSS in the band 11.7–12.5 GHz, for Regions 1 and 3. The Plan assigned five channels to each country, with a channel spacing of 19.18 MHz. It was based on FM/TV systems (PAL, SECAM, NTSC) with 13.5 MHz/V frequency deviation and 27 MHz receiver bandwidth. The protection ratios are 31 dB (co–channel, CCI) and 15 dB (adjacent channel, ACI).

For the case of Italy, a satellite eirp (effective isotropic radiated power) of about 64 dBW at the beam centre was assigned in order to guarantee a carrier–to–noise ratio (C/N) of 14 dB (in 27 MHz) at the –3 dB area contour for 99% of the worst month, assuming a receiving system with a 90–cm antenna and a figure–of–merit (G/T) of 6 dB/°K. This C/N value is necessary to achieve adequate service quality with analogue FM/TV systems. The 64 dBW eirp requires the use of a high–power travelling–wave tube amplifier TWTA (at least 230 W for Italy) on the satellite.

Receiving systems currently available on the market having a noise figure (NF) = 1.5 to 1.2 dB and 60–cm antenna with 70% efficiency, offer significantly better performance; they allow for a G/T of 13.5 dB/°K in clear sky. With WARC'77 eirps, C/N values of 19 dB and 16.9 dB are then achievable in Italy (climatic zone K) for 99% and 99.7% of the worst month, respectively. Further improvements are expected with the next generation of receivers (NF = 0.8 dB), soon to be available on the market.

Technology progress in receiving antennas is also very promising. For example, modern 50–60 cm receiving antennas show an improved radiation pattern, providing the same protection against interference as was assumed by the WARC'77 Plan for 90–cm dishes.

Significant improvements have also been made in satellite technology. Today, improved power supply performance permits continuous operation under eclipse conditions, allowing exploitation of a wider arc of orbital positions. Shaped–beam technology can be employed to cover the service area efficiently, with perhaps only 1 dB variation in eirp, and to provide a geographical isolation capability not feasible with a simple beam.

Finally, the progress of receiving systems and satellite technology allows a significant relaxation of the satellite power with respect to the WARC'77 assumptions. This is the key of the success of DTH (direct–to–home) television services via medium–power pan–European telecommunications satellites (e.g. Eutelsat II, Astra) in the FSS band, which are no longer penalised by their relatively low eirps. A large number of television programmes are now available in Europe from these satellites, either directly or through cable distribution networks.

This new scenario has stimulated the need for a modernisation of the WARC'77 Plan in order to fulfil the increasing demand for new programmes with supranational and pan–European coverages and offers the prospects of more efficient utilisation of the spectrum and orbit resources (Resolution 524 of WARC'92).

The adoption of digital techniques allows improvements in the *capacity* without changing the Plan [3, 4], whilst complying with the required protection ratios for analogue TV/FM systems and allowing a significant eirp reduction. In fact (*Section 5*), each one of the five WARC'77 channels assigned to a service area could provide up to four EDTV programmes (enhanced–definition television) or even eight SDTV programmes (standard definition television), time–multiplexed on a single digital carrier, as an alternative to one HDTV programme. The *flexibility* of the Plan, such as the use of supranational service areas or the reduction of the satellite spacing in orbit, could be

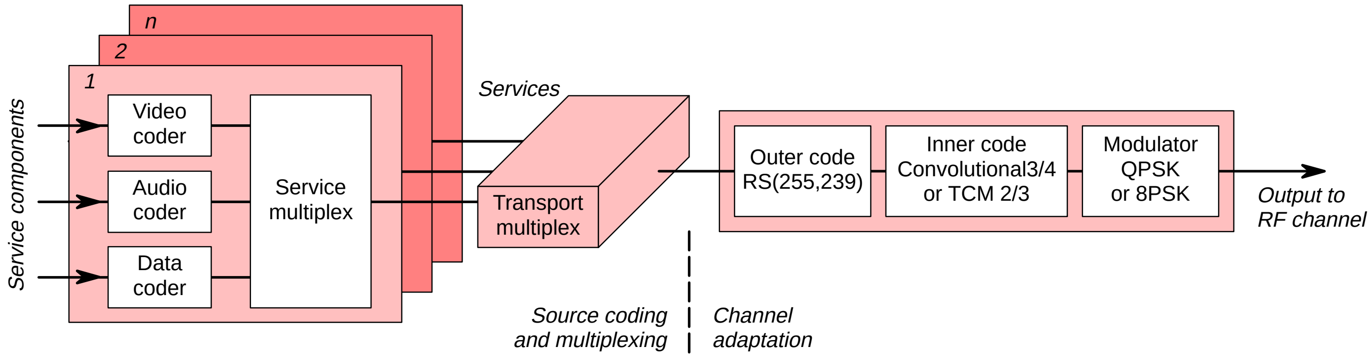


Figure 1
Block diagram of a digital television transmission system.

significantly facilitated by the adoption of digital systems, requiring lower protection ratios than analogue FM systems.

In the case of a radical re–planning of the 12 GHz BSS band for digital services, with the introduction of the concept of a "single frequency plan" already proposed for the 22 GHz band, the full 800–MHz band could be allocated to each service area, on both polarizations, simply by exploiting the orbital separation of the satellites and the geographical separation of service areas. In this case, a total of 40 RF channels, each 40 MHz wide, would be available per service area on each of the two polarizations.

2.2. *Perspectives of W–HDTV BSS at 21.4–22 GHz*

The WARC'92 allocated the frequency band 21.4–22 GHz to the broadcasting satellite service for W–HDTV in Regions 1 and 3. These results have stimulated several European organizations to join in a project, called HD–SAT, as part of the European Communities RACE II programme (Research and Development in Advanced Communication Technologies in Europe). HD–SAT began in 1992, for a duration of 3 to 4 years, and intends to prove the technical feasibility of bandwidth–efficient coding and modulation digital systems for W–HDTV satellite broadcasting in the "Ka" band (30/20 GHz) with picture quality which is virtually transparent to the HDTV studio production system. Other key elements are compatibility and inter–working with the terrestrial infrastructure including cable, MMDS and ATM networks.

Receiver technology at 22 GHz is rapidly improving. Low–noise downconverters (LNC) at 21.4–22 GHz have been developed for the consumer market, using low–cost packaged components based on GaAs HEMTs. A noise figure of 1.6–1.7 dB is achievable, with a conversion gain higher than 60 dB. These technological improvements increase the perspectives for the future utilisation of this new frequency band for W–HDTV BSS.

3. *Satellite digital television: technical factors*

The adoption of a digital solution offers significant advantages:

– high and constant quality and service reliability;
– ruggedness against noise and interference;
– spectrum efficiency (e.g. by frequency re–use) and planning flexibility;
– reduction of the satellite power;
– flexibility of the multiplex for different service configurations (e.g. multi–programme television or HDTV).

The overall service quality depends jointly on the intrinsic performance of the picture coding algorithm and on the service availability. The optimisation 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 on the satellite channel. *Fig. 1* shows a conceptual block diagram of the transmitting part of a digital multi–programme television system. In the case of HDTV, the full multiplex capacity is allocated to this service.

The satellite channel, in contrast to terrestrial broadcast and cable channels, is basically non–linear and wide–band. The non–linearity is due to the amplitude and phase characteristics of the on–board TWTA, which is operated close to saturation in order to optimise the power efficiency.

The optimisation of the satellite transmission system for multi–programme television and HDTV requires careful consideration of several technical factors:

– minimum bit–rate per programme required to provide various levels of picture quality ranging from conventional television up to HDTV;

– performance requirements in terms of C/N, C/I and bit–error ratio (BER);

– suitable modulation and channel coding techniques and usable transmission capacity;

– interference compatibility with analogue FM/TV systems (e.g. PAL, D2–MAC) in a hybrid digital/analogue scenario;

– constraints due to the need for commonality with terrestrial digital TV/HDTV services on broadcast channels and cable networks.

3.1. Progress in video compression techniques

The remarkable achievements of video compression systems based on the use of hybrid DCT (discrete cosine transform), motion compensation and entropy coding have allowed CMTT and ETSI to accomplish the standardization of codecs for the transmission of conventional definition television at 34 and 45 Mbit/s for contribution purposes. The CMTT activity is now focused on the definition of a standard for secondary distribution and broadcasting. The basic scheme of the systems under study is similar to that adopted in the European project EU–256, which has had a pioneering rôle in digital television and HDTV.

Recent results of computer simulations at the RAI Research Centre [5] and other laboratories involved in the standardization activities (e.g. in EU–625/Vadis and ISO/MPEG–2) seem to indicate that a subjective quality virtually transparent to the studio standard (CCIR Recommendation 601) can be achieved with a bit–rate of about 0.9 bit/pel, while visible impairments are expected for some programme material at 0.4 bit/pel. These compression ratios, corresponding to about 9 Mbit/s and 4 Mbit/s respectively, seem to be adequate for 625–line television signal coding with picture quality corresponding to CCIR Recommendation 601 and to conventional composite television signals (PAL, SECAM). With the addition of some capacity for high–quality sound, data services and error correction by Reed Solomon RS(255,239) code, gross bit–rates of about 11 Mbit/s and 5.5 Mbit/s are therefore necessary for EDTV and SDTV.

At a gross bit–rate of 45 Mbit/s, high–quality HDTV can easily be supported by satellite channels. In Europe, in the 8–MHz bandwidth of the UHF terrestrial channels, a bit–rate of about 30 Mbit/s is currently being considered for multi–programme television and HDTV [2].

The advanced stage of the ISO/MPEG–2 standard definition has recently pushed several companies in Japan, North America and Europe into developing products very rapidly using this standard. Particularly interesting, in this context, are applications such as satellite delivery–to–home of multi–programme digital television services. Various different quality levels are being considered in Europe [2]: EDTV (16:9 aspect ratio, CCIR Recommendation 601), SDTV (equivalent to PAL and SECAM quality) and LDTV (equivalent to VHS quality). Multi–programme high–quality sound, subscription, pay–per–view and high–capacity data services are basic features. The time scales for the introduction of these new services are very tight. The possible evolution to HDTV is foreseen in a longer–term perspective, mainly because of the lack of flat–panel high–resolution displays and low–cost decoders for the consumer market.

3.2. The transport multiplex

The definition of a common multiplex for the transport on various media, such as satellite, terrestrial VHF/UHF channels and cable networks, is fundamental for the success of the future digital television/HDTV services. The multiplex should be flexible in order to carry the different services (e.g. video, sound and data), and should allow easy access to the various components by means of a service identification channel.

For broadcasting applications, the multiplex must be rugged against errors, in order to allow reliable system performance under critical receiving conditions. This can be achieved using fixed–length information units (packets), which allow robust synchronization in the receiver.

Additional ruggedness can be provided by grouping packets into fixed–length frames (framed multiplex). Inside a frame, the addressing function is carried out by assigning fixed packet positions to each service, the assignments being reconfigurable only by transmitting suitable look–up tables. This method, adopted in the MAC/packet and DAB multiplexers, offers correct demultiplexing under error conditions, and in addition requires only limited transmission overhead for the packet headers. An alternative solution, which avoids demultiplexing errors, while also preserving the flexibility of a "random" packet multiplex, is to include a powerful error–correcting code in the packet address. For example, the (23,12) triple–error correcting Golay code, adopted by the MAC/packet system, assures less than one packet loss every several years, at an input BER of 10^{-4}, on the assumption of independent errors.

Advanced modulation and channel coding systems proposed for satellite and terrestrial television broadcasting often make use of a two–level concatenated error–protection scheme, based on a convolutional code (inner code) and a Reed–Solomon code RS (outer code) (*Section 3.3.*). The two protection levels are separated by a suitable interleaving process to randomise the errors after Viterbi decoding. The RS decoder can be associated with the demodulator, in order to protect the total data–stream entering the demultiplexer, or after the demultiplexer, at the level of each individual service component. The error rate after Viterbi decoding, at the system C/N threshold, is between 10^{-3} to 10^{-4}. The corresponding error–rate after RS decoding is in the region 10^{-6} to 10^{-11}. Therefore, in order to improve the reliability of the demultiplexer in the presence of errors, the RS decoder should be associated with the demodulator, i.e. before the demultiplexer.

To cope with the difficult propagation conditions on broadcasting channels, whether they be terrestrial VHF/UHF channels or satellite channels in the 22–GHz frequency range, hierarchical modulation and channel coding techniques have been proposed. These techniques allocate different error–protection levels according to the importance of the data–streams, so that the bit–error rate is not homogeneous in the various data–streams. This situation is still more demanding in terms of multiplexer ruggedness against errors, because the demultiplexing process must operate properly even when part of the data–streams are completely un–usable. This situation currently occurs in the case of portable receivers which cannot make use of directive antennas.

3.3 Channel coding and modulation

The successful introduction of satellite digital television requires the adoption of advanced transmission systems in order to minimise the satellite power requirements while permitting the use of small receiving antennas. Suitable modulations are QPSK (2 bit/s/Hz) and 8PSK (3 bit/s/Hz) which allow the TWTA to operate close to saturation, i.e., at its maximum power. Higher–order modulations, such as 16QAM and 32QAM (4 and 5 bit/s/Hz), proposed for terrestrial television broadcasting to achieve higher spectrum efficiency, are not power–efficient because they require the TWTA to operate significantly below its nominal power (i.e. 5 to 6 dB output back–off, OBO), in a quasi–linear condition [6].

The following channel coding schemes, offering a wide range of spectrum and power efficiencies, have been considered [3, 4]:

- System A: QPSK rate 3/4
- System B: TC–QPSK rate 7/8
- System C: TC–8PSK rate 2/3
- System D: TC–8PSK rate 5/6

System A is obtained by "puncturing" a rate 1/2, constraint length 7, convolutional code. System B is a trellis coded (TC) QPSK system, using a punctured rate 3/4 and suitable mapping in the signal space. Systems C and D are based on the "pragmatic" trellis coding approach [7] and 8PSK modulation, making use of a rate 1/2 and 3/4 code, respectively. In all cases, error protection is provided by concatenating the Reed–Solomon RS(255,239) "outer" code with a convolutional or trellis "inner" code associated with the digital modem. The same "industry standard", rate 1/2 Viterbi decoder already available on the market, can be used in all solutions.

A typical BSS satellite chain, including the digital modulator, the satellite TWTA, the OMUX filter, with 38.4 MHz bandwidth at –3 dB, and an ideal demodulator has been simulated by computer. The optimised TWTA operating point was OBO = 0 dB for QPSK and OBO = 0.3 dB for 8PSK. The following notations are adopted:

R_u (Mbit/s) = useful HDTV bit–rate, including video, sound, data and RS(255,239) redundancy;

R_s (MBaud) = modem symbol–rate, corresponding to the Nyquist bandwidth of the modulated signal (–3 dB bandwidth).

Fig. 2 shows the BER versus E_b/N_o curves after Viterbi decoding achieved by simulation on the satellite chain.

Table 1 summarises the systems' performance on a linear channel with additive white Gaussian noise (AWGN) and on the non–linear satellite channel, in terms of E_b/N_o at BER = $2x10^{-4}$ at the Viterbi decoder output. This BER figure allows a residual BER of about $1x10^{-11}$ to be achieved after error correction by RS(255,239) code, corresponding to high–quality (HQ) pictures. Studies

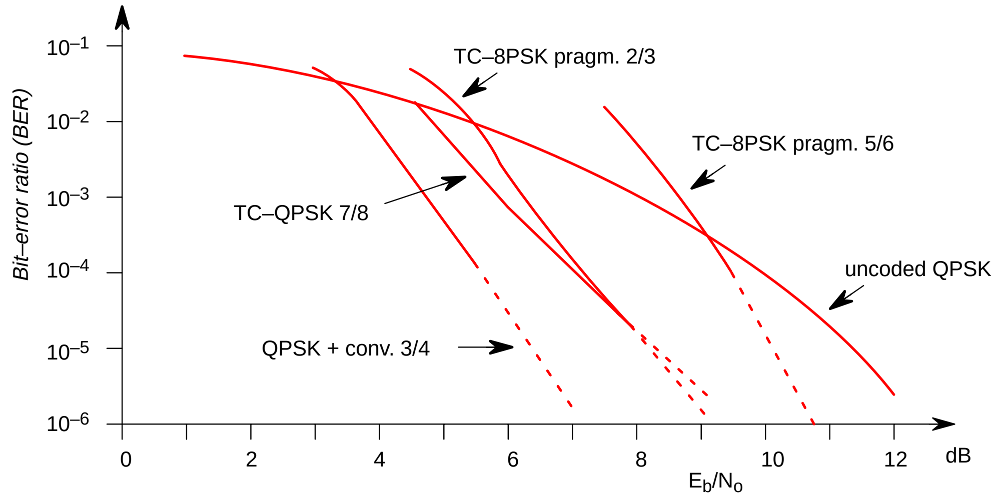


Figure 2
Comparison of the performance of various modulation schemes suitable for digital TV/HDTV by satellite.

[4, 8] on the error statistics after Viterbi decoding have shown that a symbol interleaving depth between 4 to 10 is required to optimise the error–correction efficiency of the RS code. The last column of *Table 1* gives the required C/N ratio in 30 MHz for high–quality pictures, at the symbol–rate R_s of 30 MBaud, which is the maximum usable value in the WARC'77 Plan and in the 36 MHz Eutelsat transponders (see *Section 5* and *Appendix 1*). The C/N figures include margins for system implementation (1.5 dB) and interference degradation (1 dB).

From *Table 1*, the optimum system in terms of power efficiency is QPSK 3/4, but it has the penalty of limited spectral efficiency. TC–8PSK 2/3 offers higher spectral efficiency compared to both QPSK 3/4 and TC–QPSK 7/8, but at the expense of increased receiver complexity (8PSK demodulator) and reduced performance on the satellite channel. TC–8PSK 5/6 allows the transmission of up to 75 Mbit/s at the symbol rate of 30 Mbaud, but it requires higher satellite power.

Systems based on QPSK modulation are easier to implement than systems based on 8PSK which, in addition, require a larger implementation margin. VLSI single–chip soft–decision Viterbi decoders for rate 1/2 convolutional code are already available on the market for a maximum clock rate of 45 MHz. This decoding speed is sufficient for all the systems of *Table 1*, because the trellis–coded systems present uncoded bits which are not processed by the Viterbi decoder. Single–chip Viterbi decoders for "pragmatic" trellis–coded 8PSK rate 2/3, at a maximum bit–rate of 50 Mbit/s, have been developed recently. Single–chip RS(255,239) coder/decoders are also available for bit–rates in excess of 160 Mbit/s. The next step could be the development of fully digital modems for TV/HDTV applications based on the advanced solutions currently adopted in digital transmission at the intermediate data rate (IDR) on communications satellites.

3.4. Use of OFDM modulation by satellite

OFDM (orthogonal frequency division multiplex) is a multi–carrier modulation method [9] which is particularly suitable for terrestrial broadcasting and cable distribution because of its inherent ruggedness against linear distortions caused by multipath propagation and by mis–matching in coaxial cable networks.

Table 1
Performance of digital systems at R_s = 30 MBaud, for BER = 2×10^{-4}.

Modulation system	R_u (Mbit/s)	Spectral efficiency (%)	E_b/N_o (dB) at BER = 2×10^{-4}		Required C/N (dB) at BER = 2×10^{-4} (See *Note*)
			Additive white gaussian noise	Satellite	
QPSK (uncoded)	60	100	8.0	9.3	14.8
QPSK 3/4 punctured convolutional code	45	75	4.3	5.3	9.6
TC–QPSK 7/8	52.5	87.5	5.4	6.6	11.5
TC–8PSK 2/3	60	100	5.4	6.9	12.4
TC–8PSK 5/6	75	125	7.4	9.3	15.8

Note: Including a 2.5 dB implementation and interference margin.

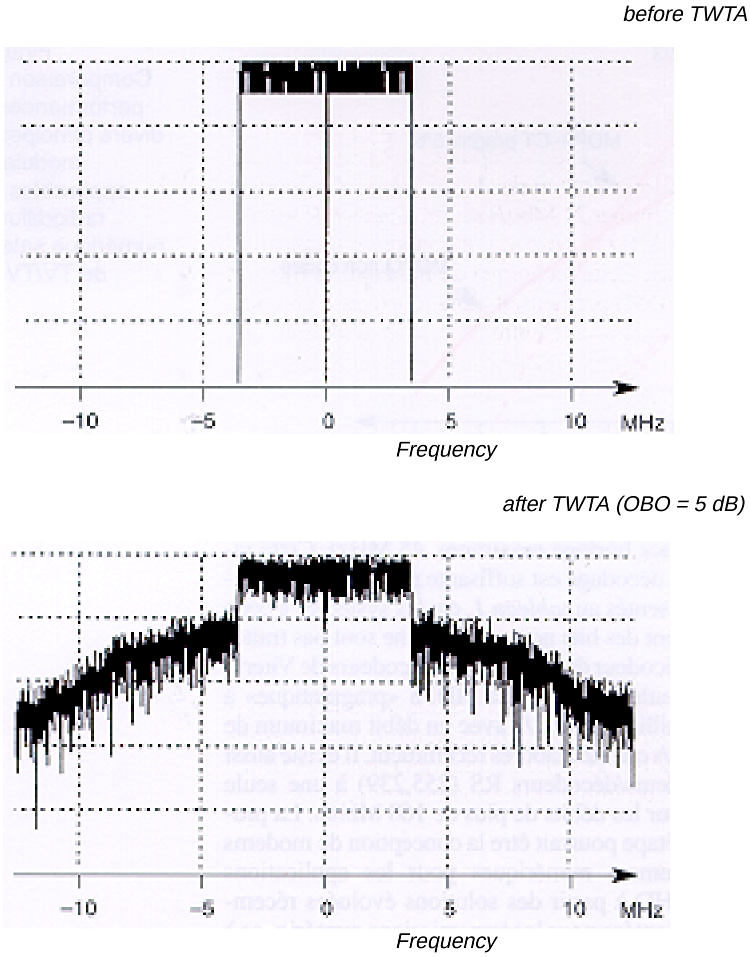


Figure 3
OFDM spectrum before and after the satellite TWTA.

OFDM will be adopted for digital audio broadcasting (DAB) and is currently being proposed in Europe for terrestrial digital television in the 7–8 MHz channels of the VHF/UHF bands. Its possible adoption also on satellite channels, which are typically "nonlinear", would allow maximum receiver commonality on the various transmission media. The need to assess the suitability of OFDM for use on satellite channels, as an alternative to the well–established single–carrier (SC) digital modulation systems, is therefore an important technical issue. It is important to note that single–carrier systems and OFDM, using the same modulation scheme on each individual subcarrier (e.g., QPSK, 8PSK), have similar spectrum efficiency.

Computer simulations have been carried out in order to compare the performance of OFDM with SC systems in a non–linear satellite chain, assuming the same modulation and coding scheme for error–protection, coherent demodulation and the same bit–rate.

The following OFDM parameters have been adopted for this study: 700 useful carriers, 1024 FFT samples, 100 µs symbol duration, no guard interval.

In order to allow direct transparency with terrestrial television services, the same RF bandwidth occupation (e.g., a single "block" of 7 MHz) is assumed for the OFDM signal on the satellite channel. It is then possible to allocate, in a 33–36 MHz satellite transponder up to four 7–MHz OFDM "blocks" by frequency–division multiplexing (FDM) (see *Section 4.*). However, because of the TWTA non–linearity, each OFDM signal suffers from additional degradations due to mutual spectrum interference between adjacent blocks.

Independently of the modulation adopted on each subcarrier (QPSK, 8PSK, etc.), the OFDM signals present a variable envelope distribution, of Rayleigh type, which is compressed by the non–linear characteristics of the on–board TWTA. The main effect of the non–linearity in the frequency domain is spectrum spreading (*Fig. 3*), which can be limited by introducing a suitable output back–off (OBO) at the TWTA. With 5 dB OBO the spectrum side–lobes are about 20 dB below the useful signal spectrum. On the time–domain constellation, the non–linearity effect is a noise–like dispersion of the transmitted points.

The TWTA operating point must therefore be optimised to reduce the distortion effect (i.e., adoption of large OBO) without penalising the transmitted power (i.e., adoption of reduced OBO).

Table 2 compares the performance of a single OFDM block and a single–carrier system, on the simulated satellite channel, assuming the same useful bit–rate (R_u).

Table 2
E_b/N_o degradation of OFDM compared to single–carrier systems.

Modulation (OFDM and single–carrier)	Bit–rate (R_u) in 7 MHz bandwidth (Mbit/s)	TWTA OBO (optimum) (dB)	E_b/N_o degradation (δ) (dB)
QPSK (uncoded)	14	4	5.6
QPSK 1/2	7	1	2.7
QPSK 3/4 punctured convolutional code	10.5	1	3.3
TC–8PSK 2/3	14	3	4.2

The performance of OFDM, compared to the single–carrier systems, for a BER of $2x10^{-4}$ (after Viterbi decoding), is given in terms of the overall E_b/N_o degradation, denoted by δ. This degradation includes the effects of non–linear distortions, power losses due to TWTA non–linearities and (OBO), and mutual interference between OFDM subcarriers.

The results of *Table 2* show that digital systems based on OFDM allow significantly lower power efficiency with respect to single–carrier systems, with the same useful bit–rate. About 3 dB to 4 dB of satellite power increase is necessary with OFDM systems using QPSK rate 3/4 and TC–8PSK 2/3 to achieve the same BER performance as a single–carrier system.

The required satellite power progressively increases moving from low to high spectrum–efficiency modulations on the OFDM carriers, i.e. from QPSK 1/2 (R_u = 7 Mbit/s), to TC–8PSK 2/3 (R_u = 14 Mbit/s). Higher–level modulations, such as TC–16QAM rate 3/4 and 16QAM, allow the best exploitation of the terrestrial channel capacity (R_u=21 and 28 Mbit/s in 7 MHz), but are not suitable for satellite transmission whether they use OFDM or a single carrier. The required C/N ratio, in 30 MHz, for OFDM/TC–16QAM and OFDM/16QAM is of the order of 16 dB and 25 dB, respectively, including 2.5 dB of implementation margin. These figures are significantly higher than the 6–8 dB of C/N required by single–carrier QPSK 3/4 systems at the same useful bit–rates.

The OFDM performance is further impaired in the case where several OFDM blocks of 7–MHz bandwidth (up to four) are carried in the same transponder by FDM techniques to exploit the bandwidth resources (36 MHz), because of the mutual interference between the blocks.

Recent studies in the framework of the HD–SAT project seem to indicate that adaptive non–linear equalization of OFDM signals could significantly reduce these E_b/N_o penalties, but at the cost of doubling (at least) the OFDM demodulator complexity, which is already at the limit of today's technology.

The use of FM modulation combined with OFDM/TC–16QAM would provide an interesting solution for satellite transmissions, allowing operation with the TWTA at saturation, thanks to the constant envelope of the FM signal. A common OFDM demodulator with 7 MHz bandwidth could then be used for terrestrial, cable and satellite receivers, the latter with an additional FM demodulator. Preliminary simulation results, not yet optimised, indicate that a C/N ratio (in 30 MHz receiver bandwidth) of about 12.5 dB (BER = $2x10^{-4}$ after Viterbi decoding) would be required to convey 21 Mbit/s on a 36 MHz satellite transponder, including a 2.5 dB implementation margin. This hybrid modulation technique (FM/OFDM) would then allow a reasonable compromise between the need for receiver commonality and transparent inter–working between different transport media. However, the satellite service would be heavily penalised both in terms of transmission capacity and power efficiency. In fact, by using an SC–QPSK 3/4 system it is possible to operate in a 36–MHz satellite transponder at the useful bit–rate of 45 Mbit/s, instead of 21 Mbit/s, with a required C/N ratio (in 30 MHz) of about 10 dB (see *Table 1*).

In the light of these investigations it can be concluded that, particularly on low/medium–power satellites, the OFDM approach, currently proposed for terrestrial television services, does not seem to allow satisfactory solutions.

4. Access to the satellite transponder

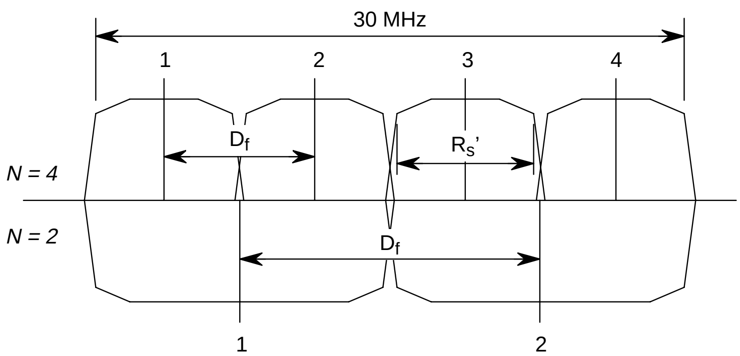
Two methods can be envisaged to access the satellite transponder with multi–programme television services:

time–division multiplex (TDM), assembling the television programmes on a single modulated carrier;

frequency–division multiplex (FDM), sharing the satellite bandwidth by several independent digital carriers, each carrying one or more television programmes

The first approach (TDM) gives the optimum performance in terms of satellite power efficiency, since near–constant–envelope modulations can be adopted (e.g., QPSK, 8PSK), allowing the TWTA

Figure 4
FDM carrier configuration.



to operate close to saturation. However, this solution implies operational constraints because all the service components must be conveyed to the site where the multiplex is assembled and the signal up–linked.

The second approach (FDM) is more flexible as regards the up–link requirements and could be advantageous in terms of commonality for direct distribution of satellite digital signals in cable networks, with a channel bandwidth of 7 to 8 MHz. However this approach inherently does not provide a resulting signal having a constant envelope. It is then necessary to operate the TWTA in a quasi–linear region, which implies reducing the system power efficiency. In addition, the future evolution from multi–programme television to HDTV would become more complex, as it would be necessary to change the transmitted bit–rate and to merge FDM channels.

The two approaches have been simulated on the same satellite channel as described in *Section 3.3*, assuming a 38.4–MHz OMUX filter. 2 and 4 carriers (denoted by N), with QPSK rate 3/4 (system A), have been allocated per transponder. Each signal carries a bit–rate $R_u' = (R_u / N)$, where R_u is the total useful bit–rate in the transponder. As shown in *Fig. 4*, to maintain an interference level on the adjacent channels which is similar to that of a single–carrier system at R_s= 30 Mbaud, the –3 dB RF bandwidth of the FDM ensemble has been set to 30 MHz. Therefore the N carriers are spaced by $D_f = (R_s–R_s')/(N–1)$, where R_s' is the symbol rate of each FDM carrier.

After an optimisation process, a global input back–off (IBO) of 4 and 6 dB, corresponding to 0.5 and 1 dB OBO on the TWTA, have been adopted for N = 2 and 4, respectively. The corresponding input back–off per carrier is (IBO+ 10 log N) dB.

Table 3 gives the E_b/N_o degradation δ at BER = $2x10^{-4}$ (after Viterbi decoding) of the FDM approach, compared to the TDM approach at the same total bit rate $R_u = N R_u'$. The degradation includes the effects of linear and non–linear distortions, power losses with respect to the TWTA saturation power, and mutual interference between carriers.

For two digital carriers (N = 2) at 17 Mbit/s, the FDM approach requires a 2.3–dB increase of satellite power with respect to a 34–Mbit/s TDM single–carrier system, for the same service availability. The satellite power should be increased by 3.3 dB in the case of two carriers at 22.5 Mbit/s (45 Mbit/s total bit–rate). In the case of four carriers (N = 4) at 8.5 Mbit/s per carrier, the power penalty is 5.8 dB.

For an assigned satellite power, the E_b/N_o degradation of the FDM approach could be overcome by a corresponding increase of the receiving antenna diameter (i.e., an additional 30%, 46% and 95%, respectively for the three cases considered above).

From these results it is possible to conclude that the TDM approach to access the satellite transponder is significantly more power–efficient than the FDM approach, expecially when four FDM digital carriers are considered. In this case, TDM is particularly suitable for direct–to–home services using small receiving antennas (50 – 60 cm). On the other hand, FDM at 4 x 8.5 Mbit/s could be interesting for multi–programme television distribution to cable network head–ends, equipped with large receiving antennas, because each FDM carrier, with QPSK 3/4 modulation, can be distributed in 8–MHz cable channels. This would allow simple frequency conversion without the need of re–modulation (see *Section 7*).

5. Interference considerations and transmission capacity

5.1 Low and medium power satellites

In Europe, Eutelsat II telecommunications satellites carry 36/72 MHz transponders (see the channel matrices in *Fig. 5*), in the Ku–band (14/11 GHz), and they are suitable for digital transmissions at 60/120 Mbit/s with QPSK modulation. On the 72 MHz transponders, TDMA telecommunication services at 120 Mbit/s are in regular operation. The 36 MHz transponders are particularly suitable for the distribution of digital television for supra–national coverages. A transmission capacity of 45 Mbit/s or 60 Mbit/s can be used with QPSK 3/4 (System A) or TC–8PSK 2/3 (System C), respectively. The modulation and channel coding techniques described in *Section 3.2.* (with minor modi-

Table 3
E_b/N_o degradation of FDM compared to TDM (QPSK 3/4, satellite channel, BER = $2x10^{-4}$ after Viterbi decoding).

Total bit–rate (R_u) (Mbit/s)	E_b/N_o degradation (δ) (dB)	
	N = 2 carriers	N = 4 carriers
34	2.3 (2x17 Mbit/s)	5.8 (4x8.5 Mbit/s)
38	2.4 (2x19 Mbit/s)	6.1 (4x9.5 Mbit/s)
41	2.7 (2x20.5 Mbit/s)	7.9 (4x10.25 Mbit/s)
45	3.3 (2x22.5 Mbit/s)	–

fications), combined in a flexible bit–rate modem, have been extensively studied and adopted in the European RACE Flash–TV project [8], which is focused on HDTV contribution links via 36 MHz transponders in Ku band, from transportable up–link stations. This digital system is now being implemented.

Astra satellites 1A, 1B, 1C, introduced by the Société Européenne des Satellite (SES), carry transponders with 26 MHz bandwidth. The usable transmission capacity is then about 34 Mbit/s and 44 Mbit/s, depending on the transmission system (A or C). The capacity could be further increased to about 41 Mbit/s and 55 Mbit/s in the new generation Astra satellites (1D and 1E), operating in the 11.7–12.5 GHz band (19.2°E), which will carry transponders of 33 MHz bandwidth [10]. An additional C/N degradation of about 0.4 dB can be expected if the bit–rate is increased from 41 to 45 Mbit/s (system A), in order to have the same bit–rate as are used on the Eutelsat and BSS satellites.

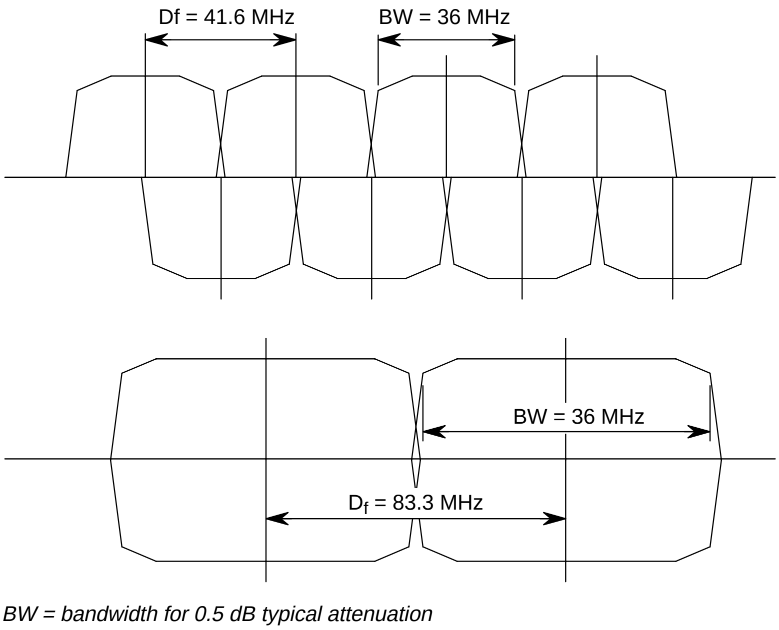


Figure 5
Eutelsat II channel matrix in the 11 GHz band
(36 and 72 MHz transponders).

5.2 BSS satellites in the WARC'77 Plan

In the case of BSS satellites at 12 GHz (WARC'77), the 27 MHz channel bandwidth is practically defined by the receiver, while the satellite OMUX is wider (usually about 50 MHz) since the five channels provided by the satellite are separated from each other by about 77 MHz (4 x 19.18 MHz). The channel matrix is shown in *Fig. 6*. A fundamental requirement for the introduction of digital television is the need to comply with the WARC'77 protection ratios (31 dB CCI, 15 dB ACI) in order to ensure coexistence with the analogue services (e.g. in PAL, D2–MAC) already in operation. It can be concluded from results of the RAI studies (see *Appendix 1*) that, with PSK modulations and raised–cosine spectrum shaping (roll–off 0.4), a maximum symbol rate of 30 MBaud is usable in the WARC'77 channels. The corresponding useful bit–rates are 45 Mbit/s and 60 Mbit/s for modulation systems A and C, respectively. The CCI protection ratios are significantly lower than the 31 dB required by the WARC'77 Plan. The ACI protection ratios are at the limits of the WARC'77 requirements (i.e., 15 dB) in the case of digital signals at 30 MBaud interfering with analogue FM, while margins of 4 dB (system C) and 6.5 dB (system A) are obtained for D2–MAC interfering with a digital signal. This gives the possibility of using satellite eirps for the digital systems which are reduced by at least 4 dB with respect to the analogue systems, which can be transmitted today at the full WARC'77 eirp. In the

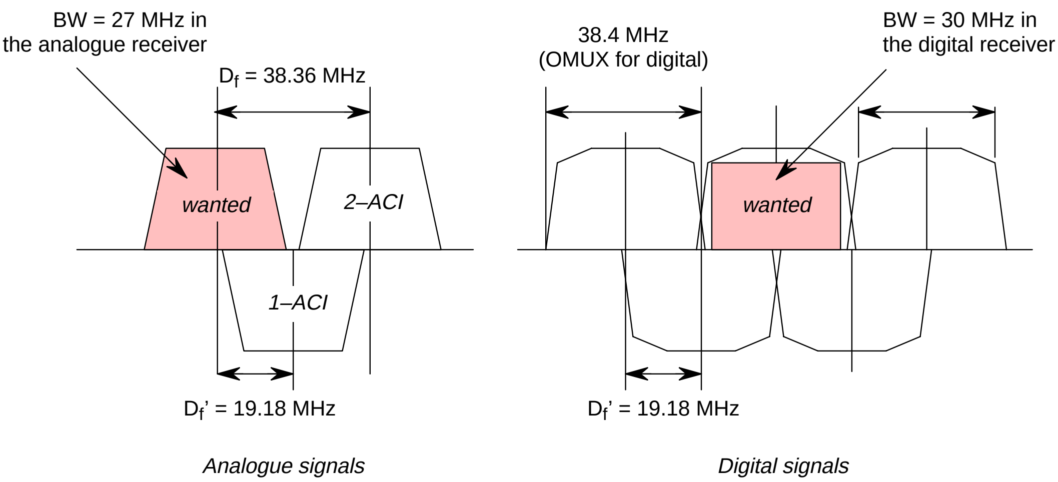


Figure 6
Possible exploitation of the WARC'77 Plan for analogue and digital television.

Table 4
Example of digital multi–programme TV/HDTV system for 12–GHz satellite broadcasting (Italy, climatic zone K).

Video coding	Hybrid DCT
Modulation	QPSK + rate 3/4 inner code
Useful bit–rate (including RS)	45 Mbit/s
Error protection RS(255,239)	3 Mbit/s
HDTV service	
video	40 Mbit/s
audio (5 MPEG–Audio stereo channels)	0.64 Mbit/s
data (teletext, service information, conditional access)	1.36 Mbit/s
Multi–programme TV service	
4 EDTV programmes	11 Mbit/s per prog.
8 STDTV programmes	5.5 Mbit/s per prog.
Required C/N ratio (in 30 MHz) for high–quality pictures (including 2.5 dB margin)	9.6 dB
Receiving antenna diameter required for high–quality pictures in 99.7% of worst month Service area: 54 dBW eirp contour	60 cm

future, in a fully–digital scenario, all the eirps of the Plan could be further reduced and the significant CCI and ACI protection ratio margins could be exploited to achieve greater flexibility in the coverage area design.

To allow interference protection on the second adjacent channels (spaced by 38.36 MHz), while operating the TWTA at saturation, a satellite OMUX filter with about 38.4 MHz bandwidth at –3 dB (see *Section 3.2.*) should be adopted. *Fig. 7* shows the spectrum of a 30 Mbaud PSK signal (2–ACI) interfering with a D2–MAC/FM signal, with and without sidelobe suppression by the OMUX.

6. Satellite digital multi–programme television and HDTV

On the basis of the results of *Sections 3* and *5*, QPSK associated with a rate 3/4 inner code is assumed as the modulation system at a gross bit–rate of 45 Mbit/s, including RS(255,239) error protection. Examples of possible service configurations of the multiplex include one HDTV programme, four EDTV programmes or eight SDTV programmes. *Table 4* gives, as an example, the main characteristics of a possible digital multi–programme TV/HDTV system based on this approach. High picture quality for the various applications (SDTV, EDTV, HDTV) should be achievable for most production material at the bit–rates of 5.5 MBit/s, 11 MBit/s and 45 MBit/s, respectively (see *Section 3.1.*).

Service availability depends on the sensitivity to errors of the picture coding algorithm and of the multiplex, and on the noise margin provided by the transmission system. For the EU–256 HDTV co–

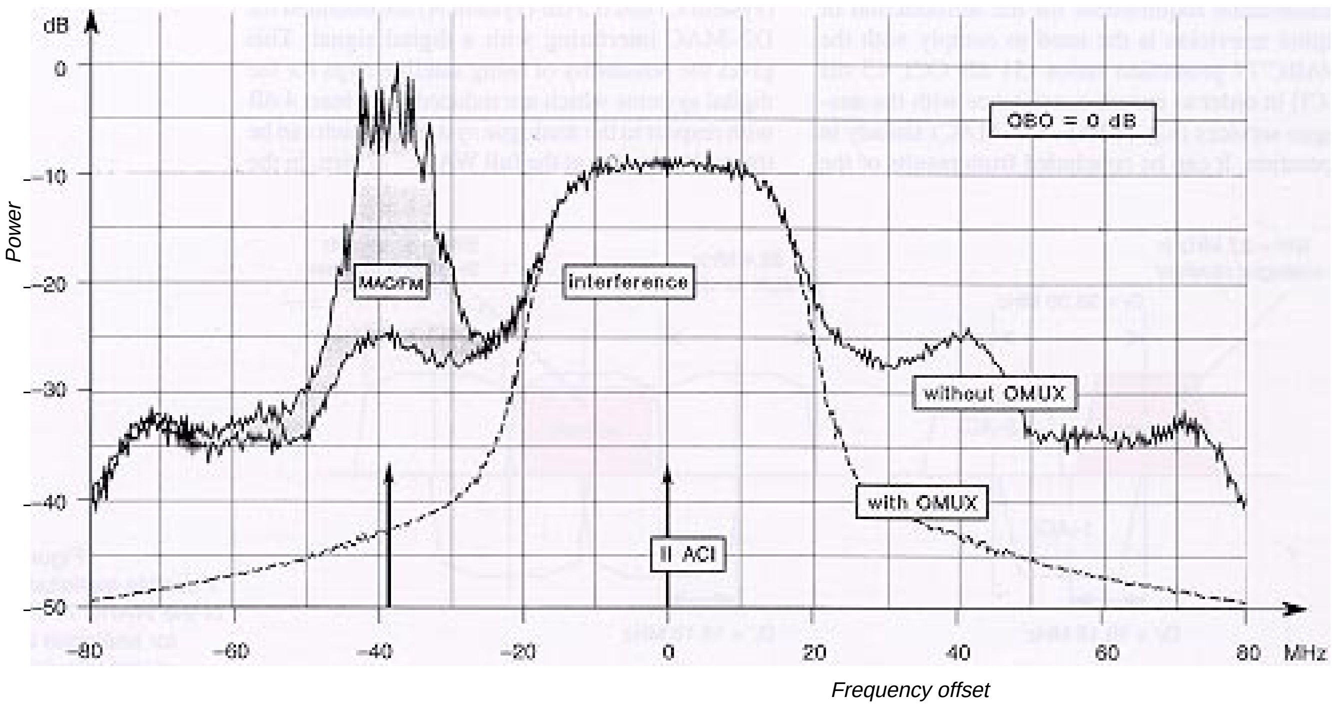


Figure 7
QPSK signal at 30 MBaud interfering with a MAC/FM signal in the WARC'77 Plan.

Table 5
Characteristics and performance of high and medium–power satellites for digital TV/HDTV broadcasting and distribution (45 Mbit/s, QPSK 3/4).

Satellite		Orbital position	eirp at beam centre (dBW)	Number of channels	Antenna diameter (cm) giving high–quality service for 99.7% of worst month	
					Beam centre	–3 dB contour
High power	TDF1 & 2, TV–SAT	19°W	64–65	5	< 40	< 40
	TELE–X	5°W	63	2	< 40	< 40
	HISPASAT	31°W	58	5	< 40	50
	EUTELSAT B (*Note 1*)	13°E	57	14	40	60
Medium power	ASTRA (*Note 2*) 1D, 1E	19.2°E	53.5	2x18	65	90
	EUTELSAT II (F1,2,3,4)	13, 10, 16, 7°E	51.5	4x9	80	110
	EUTELSAT II F6 (Hot bird)	13°E	49.5	18	100	140

Note 1: Project under examination

Note 2: The receiving antenna diameter refers to 41 Mbit/s, QPSK 3/4 signals on 33 MHz transponders

decs a maximum BER of $2x10^{-4}$ at the demodulator output (after Viterbi decoding), ensures high–quality pictures after RS(255,239) error correction (see *Section 3.2.*). At BER of $2x10^{-3}$, corresponding to a further C/N reduction of about 1 dB, the system synchronization and service continuity are lost.

The ideal service continuity target (outage time) for digital TV/HDTV systems at 11–12 GHz would be 99.9% of the worst month (corresponding to about 40 minutes of outage time); this is currently achievable by conventional FM/TV systems. In the digital system considered in the example of *Table 4* the target for high–quality picture availability is set at 99.7% of the worst month. Taking into account the typical rain attenuation statistics at 12 GHz in Italy (climatic zone K) a receiving antenna of 60 cm would be sufficient for high–quality HDTV or multi–programme EDTV/SDTV reception, for 99.7% of the worst month (BER = $2x10^{-4}$, C/N = 9.6 dB in 30 MHz, 54 dBW eirp service area contour, receiver NF = 1.5–1.2 dB, 2.1 dB C/N loss because of rain attenuation from 99 to 99.7% of the worst month). Under these conditions 99.9% service continuity (BER = $2x10^{-3}$) is practically achieved, taking into account also the quite large implementation margins assumed (i.e. 2.5 dB).

The same TV/HDTV system at 45 Mbit/s with QPSK 3/4 is suitable for use on medium–power satellites with 36 MHz channel bandwidth. In the case of Astra 1D, 1E, with 33–MHz transponders, the bit–rate should be limited to 41 Mbit/s (see *Section 5.1.*). If a bit–rate of 45 Mbit/s is adopted, the antenna diameter should be increased in order to balance the signal degradation (typically 0.5 dB C/N) due to the bandwidth limitation [10]. Alternatively, TC–8PSK 2/3 at 45 Mbit/s can be used, but with a penalty of about 1.5 dB C/N with respect to QPSK 3/4.

Table 5 compares the characteristics and performances of high–power and medium–power satellites, currently in operation or planned for future introduction, in terms of capacity (number of channels) and eirps on the axis. The last two columns give the antenna diameter for high–quality reception (99.7% of the worst month) of TV/HDTV at 45 MBit/s QPSK 3/4, at the beam centre and at the –3 dB contour. The receiving antennas are very small (40 to 60 cm) for high–power satellites at 12 GHz. Eutelsat B at 13°E should provide 14 channels, potentially usable for direct–to–home broadcasting of up to 56 (14 x 4) EDTV programmes or 14 HDTV programmes. In the case of medium–power satellites, Eutelsat II F–6 (Hot Bird) will provide up to 72 (18 x 4) EDTV programmes or 18 HDTV programmes, receivable with 100 to 140–cm antennas. Eutelsat II F1, 2, 3, 4, currently in operation, could provide a total of 144 (4 x 9 x 4) EDTV programmes (or 36 HDTV programmes), but from four different orbital positions. A similarly impressive transmission capacity will be made available by future Astra 1D, 1E satellites, from a common orbital position (19.2°E) in the BSS band (11.7–12.5 GHz). The required receiving antennas will range from 65 to 90 cm.

This evolutionary scenario of satellite television, stimulated by the introduction of digital techniques, is expected to be a reality before the end of the century. In a longer–term perspective, digital W–HDTV could be introduced in the 21.4–22 GHz band, with the same system concepts proposed for use in the 11–12 GHz band. Early studies

[6] have demonstrated the possibility of broadcasting, in the 21.4–22 GHz band, 12 W–HDTV programmes per service area at 70 Mbit/s, by exploiting the two polarizations. However, due to the severe propagation conditions at 21.4–22 GHz, a digital HDTV system exhibiting abrupt failure characteristics may not be able to provide the required service availability without a penalty on the satellite transmit power. A method to extend service continuity, without increasing the satellite power, has been developed by the CCETT. This advanced system is based on the adoption of layered modulation in conjunction with layered picture coding and layered channel coding. It provides graceful degradation from HDTV quality, achievable for most of the time, to conventional television quality during deep rain fades.

7. Distribution of digital TV/HDTV signals in cable networks

Satellite television broadcasting, although primarily focused on direct–to–home reception, requires signal distribution via large cable networks and community receiving installations serving single buildings.

The adoption of a unique modulation scheme optimised for the two transmission media, satellite and cable, is practically impossible. In effect, the satellite channel is basically non–linear and power limited, but does not suffer from stringent bandwidth limitations; cable channels are linear and allow relatively high S/N ratios, but are band–limited and are currently affected by echoes and other distortions. However, a common modulation system could probably be adopted for terrestrial broadcasting channels and for cable networks.

In Italy, the distribution of satellite signals in cable receiving installations could be done in the 8–MHz channels of the UHF bands, and/or in the extended superband (230 to 470 MHz) with 8 MHz or 12 MHz channel spacing, as foreseen for distribution of D2–MAC and HD–MAC.

At the network head–end, various technical approaches could be chosen to adapt the signal received from the satellite to the cable channels. For example:

a) demodulation, error correction, demultiplexing of each service component, conversion to PAL/

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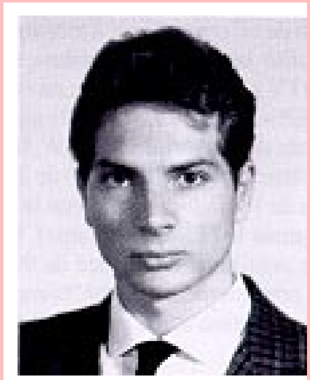
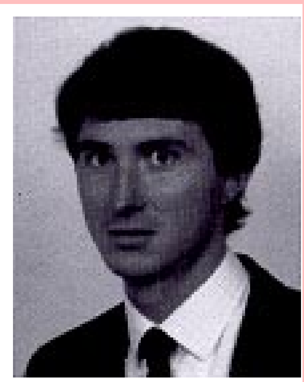
Dr. Cominetti is an active contributor to the studies of the CCIR and in recognition of this activity he was awarded the Diplôme d'Honneur 1989.



Mr. Michele Visintin *graduated in electronics engineering at Turin Polytechnic in 1987. He joined the Research Centre of RAI–Radiotelevisione in 1988 where he is involved in the analysis of digital communications systems and computer simulations.*



Dr. Alberto Morello *graduated in electronic engineering at Turin Polytechnic in 1982 and took his doctorate degree in 1987. He joined the Research Centre of RAI–Radiotelevisione Italiana in 1984 and is now in charge of the digital transmission group of the Special Technologies Laboratory. He is engaged in research on digital modulation and coding techniques for audio, data and television, and high–definition television transmission and broadcasting via satellite.*

Dr. Morello is a member of several groups in the EBU and CCIR and has authored a number of technical and scientific articles relating to his studies.

SECAM for distribution in AM/VSB (short term solution);

b) demodulation, error correction of the digital signal, digital remodulation on a single cable channel or in two merged channels;

c) demodulation, error correction, demultiplexing of the digital service components and re–assembly of reduced bit–rate multiplexes, digital re–modulation on separate cable channels;

d) in the case of FDM satellite transmission at 4 x 8.5 Mbit/s (see *Section 4.*), the four digital carriers can simply be filtered and frequency converted for distribution into four independent 8 MHz cable channels.

Suitable digital modulations for cable networks are 16QAM (spectral efficiency M = 4 bit/s/Hz), 32–QAM (M = 5 bit/s/Hz), and 64QAM (M = 6 bit/s/Hz), or their trellis–coded versions (M–1 bit/s/Hz) with Viterbi decoding. They can be associated with single–carrier (SC) modulation with adaptive equalization in the receiver or with multi–carrier OFDM modulation.

The maximum bit–rate in a single 8 MHz channel, using 32QAM (M = 5 bit/s/Hz) with sharp roll–off (0.16), is of the order of 34 Mbit/s and the required C/N ratio (in 8 MHz) is about 27 dB (including 2 dB implementation margin and 2 dB linear distortion margin after equalization).

Two 8–MHz channels could be used to convey a single digital signal at 45 Mbit/s (approach b) or two independent signals at 22.5 Mbit/s (approach c), requiring 23 dB C/N in 16 MHz with 16QAM modulation. In 12–MHz channels, 32QAM at 45 Mbit/s could be used, requiring a C/N (in 12 MHz) of 26.5 dB (with 4 dB margins).

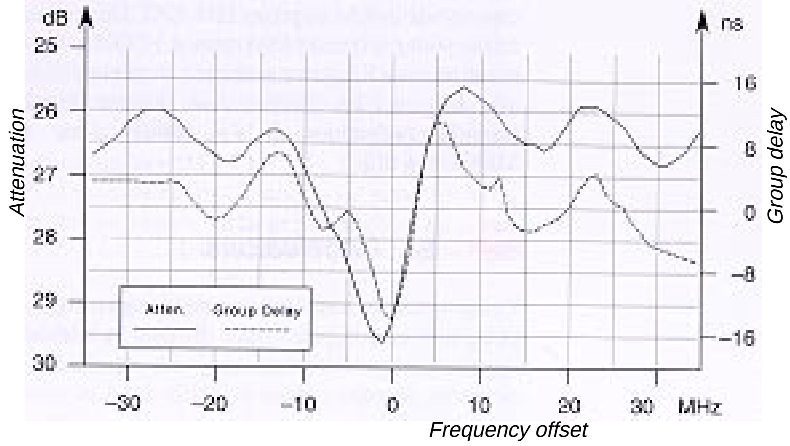
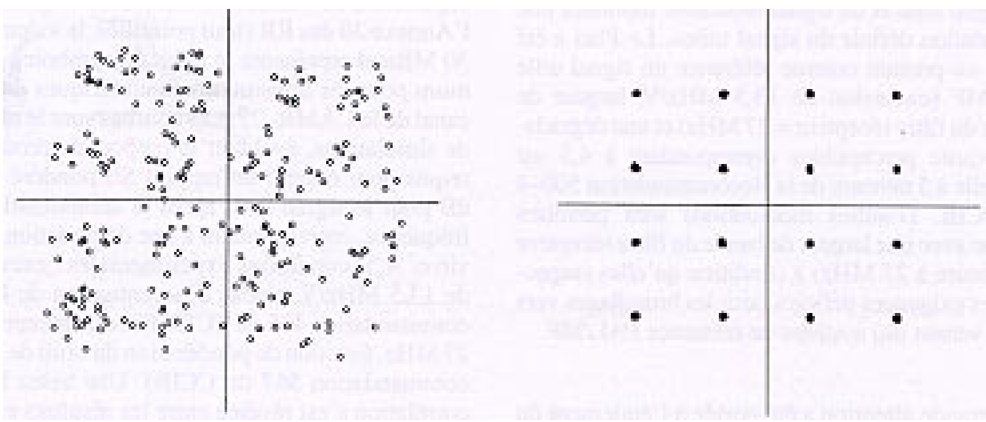


Figure 8
Typical distribution network characteristics.

Simulation results on the performance of 16QAM at 34 Mbit/s with a blind adaptive equalization (4–tap transversal filter) [4] have demonstrated the good performance of this system in the presence of typical linear distortions (see *Fig. 8*) introduced by a community antenna system. *Fig. 9* shows the 16QAM constellation with and without adaptive equalization.

8. Transmission experiments

The availability of EU–256 codecs and of a transportable feeder–link station for the Olympus satellite at 12 GHz has allowed the RAI Research Centre to carry out several transmission experiments of digital television at 17 Mbit/s and 34 MBit/s, and HDTV at 70 and 45 Mbit/s, during the past few years. The large–scale HDTV transmissions carried out during the Football Worldcup (Italia'90) demonstrated the reliability and the technical and operational feasibility of a satellite point–to–multipoint digital transmission system for high–quality HDTV programmes. HDTV transmissions at 45 Mbit/s, carried out by Retevi-



before equalization *after equalization (5 taps)*

Figure 9
Use of equalization on a domestic distribution network carrying 34 Mbit/s 16QAM signals (constellation diagrams after demodulation).

sión via Eutelsat II during the Olympic Games (Barcelona'92), confirmed these results. Recently, in the framework of the RAI participation in the HD–SAT project, the feasibility of a complete HDTV chain for transmission at 70 Mbit/s (QPSK rate 2/3) via the 30/20 GHz payload of the Olympus satellite has been demonstrated. Further field trials are planned using Olympus at 12 GHz, in co–operation with the European Space Agency (ESA), to assess the performance of a digital transmission system at 45 Mbit/s with TC–8PSK rate 2/3.

9. Conclusions

The progress of digital technology offers concrete perspectives for digital television on different distribution media (satellite, terrestrial channels, cable networks and B–ISDN). Advanced digital techniques for picture and sound coding, channel coding and modulation, have proved their efficiency and reliability in several transmission experiments, and are now entering the VLSI implementation phase. Multimedia applications of digital video technology are already becoming a reality. The availability of digital techniques, at low cost, are therefore the key to the future introduction of satellite multi–programme television services, at various quality levels: EDTV and SDTV, including the evolution to HDTV. Broadcasters, satellite operators and receiver manufactures are actively developing common plans in this direction. A suitable transmission technique to cope with the power constraints of satellite channels is based on QPSK modulation, with rate 3/4 FEC (forward error correction) with Viterbi decoding. This technique has minimal demodulation performance degradations and reasonable receiver complexity for the consumer market. Medium–power satellites are the ideal channels for the rapid introduction in Europe of these new services, allowing maximum exploitation of the transponder capacity. It is then possible to foresee, by the end of the century, a significant evolution in satellite television from the analogue to the digital world, with progressive integration of services provided by satellite channels and terrestrial digital networks. The need for harmonisation and commonality in source coding and multiplexing techniques for use on the various delivery media is the key factor for the evolution towards this future scenario.

Appendix 1
Interference compatibility of digital signals in the WARC'77 Plan

Extensive studies have been focused on the identification of the maximum symbol rate (corresponding to the –3 dB spectrum occupancy) for QPSK and 8PSK transmission in the12–GHz channels of WARC'77, while still fulfilling the interference requirements regarding analogue systems (PAL, MAC) requiring protection ratios of 31 dB (CCI) and 15dB (1–ACI).

The protection ratio PR is defined as "the power ratio between the wanted and interfering unmodulated carriers giving a pre–defined impairment in the wanted signal". The Plan was defined assuming as a reference a PAL/FM wanted signal (frequency deviation 13.5 MHz/V, receiving filter bandwidth 27 MHz), and a "just perceptible" impairment, corresponding to about grade 4.5 of the 5–grade scale of CCIR Recommendation 500–4. Other types of modulation are allowed (even with a receiving filter bandwidth wider than 27 MHz), provided that they fulfill the protection ratio requirements defined for interference to (and from) the reference PAL/FM system.

Particular attention was paid to the spectrum spreading of the digital signal at the output of the satellite TWTA, operating close to saturation. In order to reduce the interference to channels at ±38.36 MHz, a satellite output filter (OMUX) of 38.4 MHz bandwidth (at –3 dB) has been adopted.

Fig. A.1 gives the protection ratios at the visibility threshold obtained for the case of QPSK, at different symbol rates, interfering with a PAL/FM signal. Since all the curves with symbol rates up to 30 MBaud are contained in the template given in Appendix 30 of the Radio Regulation (dotted line), the value of R_s = 30 MBaud represents the maximum symbol rate usable for digital transmission in the WARC'77 channel. The curves have been obtained by computer simulations, measuring the required protection ratio to achieve a weighted signal to interference ratio of 54 dB for the PAL signal

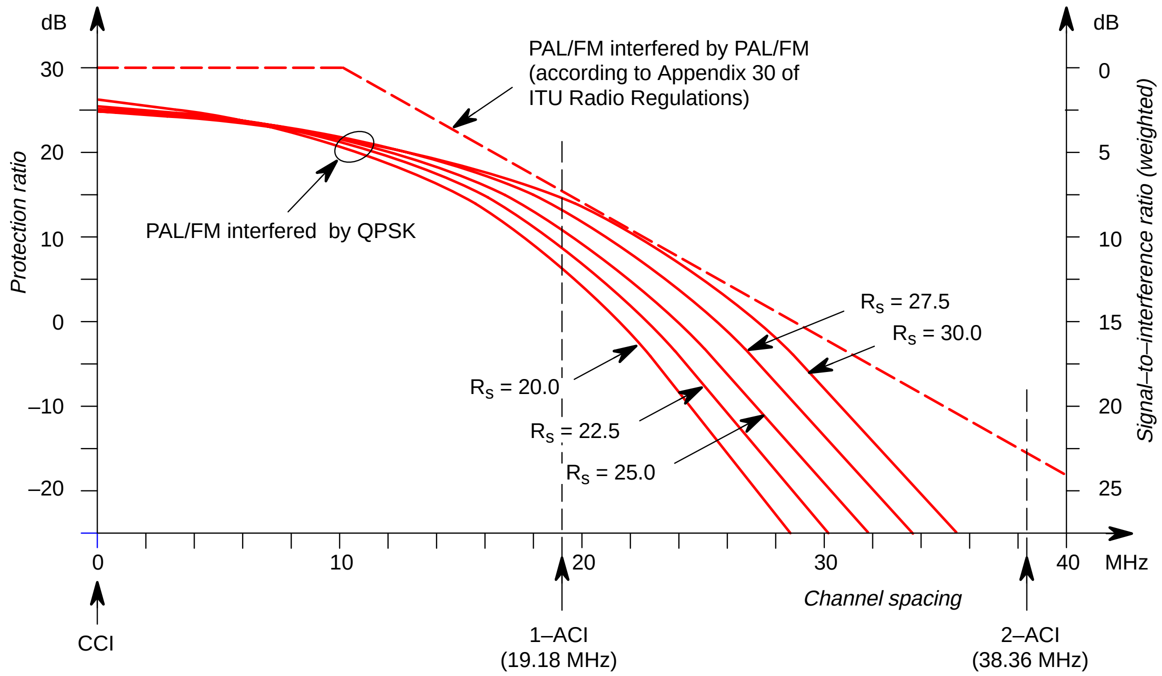
Condition	Wanted signal	Protection ratio			
		CCI (dB)	Margin w.r.t. WARC '77	1–ACI (dB)	Margin w.r.t. WARC '77
Digital vs. analogue FM	PAL	25	6.0	14	1.0
	D2–MAC	23	8.0	15	0.0
Analogue FM vs. digital	QPSK 3/4	14	17	8.5	6.5
	TC–QPSK 7/8	16	15	9.0	6.0
	TC–8PSK 2/3	17	14	11	4.0
	TC–8PSK 5/6 (see *Note*)	20	11	11.5	3.5
Digital vs. digital	QPSK 3/4	13	18	8.5	6.5
	TC–QPSK 7/8	15	16	10.5	4.5
	TC–8PSK 2/3	16	15	11.5	3.5
	TC–8PSK 5/6 (see *Note*)	19	12	14	1.0

Note: For R_s = 28 Mbaud, corresponding to R_u = 70 Mbit/s.

Table A.1. Protection ratios for analogue FM and digital systems at 30 MBauds, co–existing in a WARC'77 channel.

after FM demodulation, corresponding to an impairment grade of about 4.5 (test conditions: 13.5 MHz/V frequency deviation, CCIR Recommendation 405 emphasis network, 27 MHz receiving filter, CCIR Recommendation 567 noise weighting function). Good correspondence has been found with experimental results carried out with R_s = 20 Mbaud and 30 Mbaud.

Table A1 gives the protection ratios, and the margins with respect to WARC'77, of the digital systems at 30 Mbaud coexisting with PAL and D2–MAC at the visibility threshold [11]. The protection ratios of PAL and D2–MAC suffering interference by the digital signal have been obtained by expert subjective assessments (viewing distance 4H, "Clown" still picture) making use of a satellite simulator with TWTA at saturation to produce side–lobe regeneration of the digital signal. The protection ratios for the digital signal, when suffering interference from D2–MAC or by another digital signal, have been obtained by com-



Video impairment: 4.8 on CCIR 5–grade scale
$S/I_{weighted}$: 54 dB
C/N: 30 dB
R_S: symbol rate (MBaud)
Deviation (PAL/FM): 13.5 MHz/V

Figure A.1. Protection ratios of PAL/FM suffering interference from a QPSK signal in a catellite channel.

puter simulations, and they refer to a C/N degradation of 1 dB (at BER = $2x10^{-4}$ after Viterbi decoding) due to the interference.

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