

Digital video broadcasting over satellite (DVB-S): a system for broadcasting and contribution applications

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SUMMARY

The general system concepts for digital television transmission and broadcasting by satellite, developed within the European digital video broadcasting (DVB) Project and standardized by ETSI are described. The system (EN 300 421) is designed to provide direct-to-home (DTH) multi-programme TV services in the BSS and FSS bands and is addressed to consumer integrated receiver decoders (IRDs), as well as collective antenna systems (SMATV) and cable television head-end stations, with a likelihood of remodulation. The system operational modes have been extended in 1998 (EN 301 210) to cover also 'contribution' applications by satellite, such as conveying vision and sound material between TV studios, or from remote locations directly to the broadcaster's premises through light and portable up-link terminal digital satellite news gathering (DSNG). The exploitation of the multiplex flexibility allows the use of the transmission capacity for a variety of TV service configurations. The use of flexible and advanced error protection techniques, based on the concatenation of Reed-Solomon and convolutional codes (with Viterbi decoding), allows optimum adaptation to different satellite transponder characteristics, i.e. bandwidth and power, providing high service quality and availability with small receiving antennas (DTH applications) or transmitting terminals (DSNG applications). Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: DVB; digital television; satellite; broadcasting; modulation; channel coding

1. INTRODUCTION

The progress of digital technologies in production, transmission and emission of television is rapidly changing the established concepts of broadcasting. Figure 1 shows a typical scheme of the digital television environment, where satellite links may be used for contribution, distribution and broadcasting purposes. The availability of consumer VLSI components has significantly contributed to the rapid emergence of digital audio/video receivers based on the MPEG technique [1], which are now available on the market at affordable prices.

Direct-to-home (DTH) digital satellite television is developing rapidly in Europe in response to the emergence of new technology and the creation of a favourable commercial environment through the deregulation of the communications sector. The success of digital satellite broadcasting depends on the way programmes can provide an attractive package for the various audiences, including pay-TV offers, down-loading of multimedia information on the set-top box (STB) for

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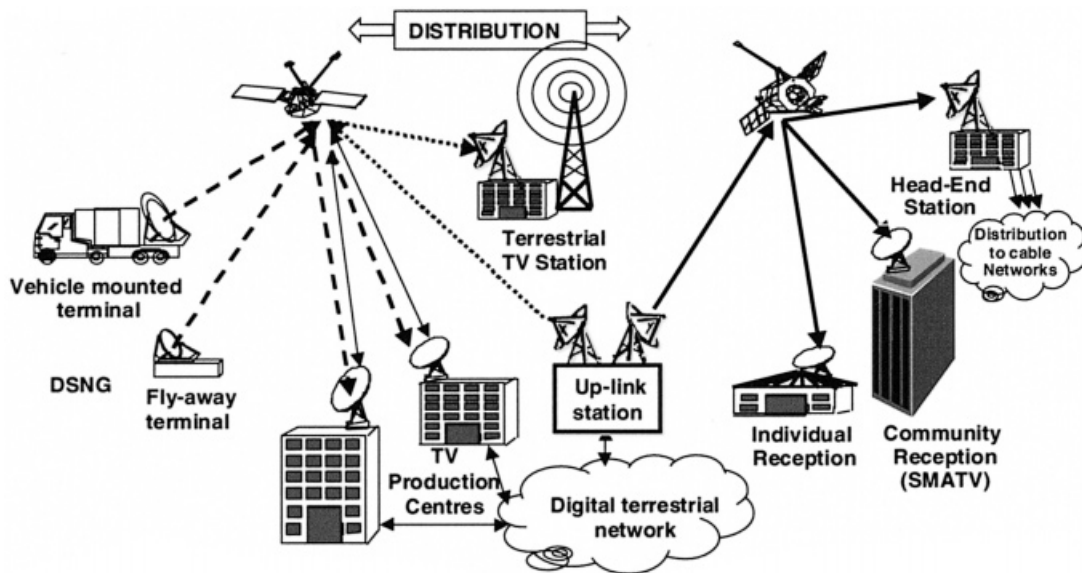


Figure 1. A typical digital television production and broadcasting environment.

local 'navigation', interactive services and electronic-commerce. The set of parameters characterizing the satellite are also important strategic factors to reach a dedicated market. The parameters to be considered are: orbital position, transponder bandwidth, power, coverage and service availability. Equally important are *technical quality* and *quantity of programmes* delivered to the users.

The progress of receiving systems and satellite technology has allowed to significantly relax the satellite power requirements with respect to the WARC '77 assumptions for the 12 GHz broadcasting satellite service (BSS) band. This progress has been dramatically accelerated after 1995 by the rapid introduction of the digital technologies, which have allowed the multiplication by factors of 5–10 of the number of TV programmes per satellite transponder. Hundreds of TV programmes are now available in Europe from medium-power pan-European telecommunication satellites in the fixed satellite service (FSS) bands, either directly or through cable distribution networks. The multiplication of the number of TV channels per transponder has offered new service opportunities, such as simultaneous transmission of a large number of football matches, multi-camera shots during car races, 'near-video-on-demand' film distribution (achieved by parallel transmission of several copies—shifted in time—of the same film).

A key role in the success of digital TV has been played by the standardization process undertaken in Europe by the DVB Project. Currently, about 250 organizations are actively co-operating in the DVB Project to identify the strategies for the introduction of digital television via satellite, cable and terrestrial channels. The television systems developed within the DVB are market-led and not just developed on the basis of the most advanced technologies. This allows to meet the requirements of all partners involved: broadcasters, satellite and cable operators and consumer electronics industry. The world-wide success of the DVB systems, already adopted in all the Continents and serving millions of house-holds, is a clear demonstration that DVB is the only global and integrated solution to digital broadcasting.

The technical studies for the definition of the DTH satellite system (usually identified as DVB-S) started within the DVB technical module (DVB-TM) in June 1993, with the co-operation of a large number of European organizations, and led to a final agreement at the end of 1993, followed by the ETSI standardization process [2]. In July 1997, the DVB-TM set up an ad-hoc group to extend the DVB-S system to better suit the contribution applications by satellite, such as point-to-point connections between studios and DSNG applications [3,8]. The so-called DVB-DSNG system is mainly based on the DVB-S system for satellite broadcasting, using QPSK modulation and convolutional coding, but other optional modulation and channel coding modes (*pragmatic* trellis coded 8PSK and 16QAM) have been introduced to increase the spectrum efficiency.

The article highlights the main features of the DVB-S and DVB-DSNG systems by satellite and the perspectives of their use on FSS and BSS satellites in Europe, focusing on the main satellite characteristics: equivalent isotropic radiated power (EIRP), transponder bandwidth, sharing of the transponder bandwidth between different signals, coverage area, transmitting and receiving antenna diameters.

2. BASIC CONCEPTS OF THE DVB SYSTEM BY SATELLITE

The DVB-S system for direct-to-home broadcasting has been optimized to cope with the basic service requirements defined by the DVB commercial module (DVB-CM): picture/sound quality flexibly selectable to cope with the service/user needs, time-division multiplexing (TDM) on a single modulated digital carrier (multi-programming, multiple channels per carrier (MCPC)), optimum exploitation of the transponder bandwidth, flexible use of the transmission capacity, operation with small receiving antennas (e.g. 60 cm), in a service area of about 51 dBW (EIRP), digital receiver (IRD) at an affordable price.

The DVB-S system has been designed with a modular structure, based on independent sub-systems, so that the other DVB systems which have been defined later (DVB-C, DVB-T) could maintain a high level of commonality with it. The MPEG-2 source coding and multiplexing sub-system is common to all the broadcasting systems, and only the 'channel adapters', providing channel coding and modulation, are specifically designed to optimize the performance on each media (satellite, cable, terrestrial).

The service requirements defined by DVB-CM for the 'professional' DVB-DSNG system were to some extent different from those defined for the broadcasting DVB-S system. In modern day broadcasting, dominated by increasing competition, a real-time acquisition of news events (e.g. sport meetings, interviews, concerts, natural calamities), in both the domestic and international environments, is a major factor in the search for audience ratings. In this context, digital satellite news gathering (DSNG), provided by light-weight up-link terminals with reduced size antennas (e.g. 90–150 cm) is the solution to establish rapid connections between outside broadcasting vans to the TV studios, often equipped by large receiving antennas. DSNG transmissions usually transfer a single TV programme in single channel per carrier (SCPC); therefore the satellite transponder is often accessed in frequency-division multiplexing (FDMA). DVB has recently defined also a digital-phone system by satellite, to achieve co-ordination for DSNG transmission [5,9]. Other requirements characterizing the DSNG system with respect to the DTH one is the 'contribution' picture quality and the need to promptly establish the satellite connection, while the limits on the receiver cost are much less stringent. Another scenario identified by the

DVB-CM is the fixed point-to-point connection of the TV studios, which can be equipped with medium-large transmitting and receiving infrastructures. In these cases power limitations are less critical than in DSNG, while higher spectrum efficiencies are required to achieve the best exploitation of the transponder bandwidth.

The key feature of the DVB transmission system, optimized through computer simulations and laboratory tests, is the capability to efficiently operate on satellite channels affected by noise, interference and distortions.

The satellite channel, in contrast to terrestrial broadcast and cable channels, is basically *non-linear, wide-band, power limited*. The non-linearity is due to the amplitude and phase characteristics of the on-board amplifier (TWTA), which for DTH applications is often operated at saturation in order to maximize the power efficiency. Conversely, linear distortions are less critical than in the terrestrial broadcasting environment and in cable networks (CATV or satellite master antenna TV (SMATV)), owing to the absence of multipath propagation and network mismatching.

The overall quality of a television service by satellite depends jointly on the intrinsic performance of the sound and picture coding algorithms and on the service availability. 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 sound and picture quality and service continuity. Hence, the optimization of the satellite transmission system for multi-programme television, often based on computer simulations [7], requires careful consideration of several technical factors:

- (a) bit-rate per TV programme required to provide various levels of picture quality ranging from conventional television up to HDTV;
- (b) performance requirements in terms of carrier-to-noise (C/N) and bit-error ratio (BER);
- (c) suitable modulation and channel coding techniques and usable transmission capacity.

The conceptual block diagram of the transmission system is shown in Figure 2: framing structure (based on the MPEG transport multiplex organization), signal randomization for spectrum shaping, advanced error protection (by concatenation of inner and outer codes), flexible coding rate, interleaving process, digital modulation. The inherent system flexibility allows trading-off between spectrum efficiency (i.e. high usable bit-rate) and power efficiency (i.e. low required C/N) on the basis of the satellite characteristics and of the service requirements.

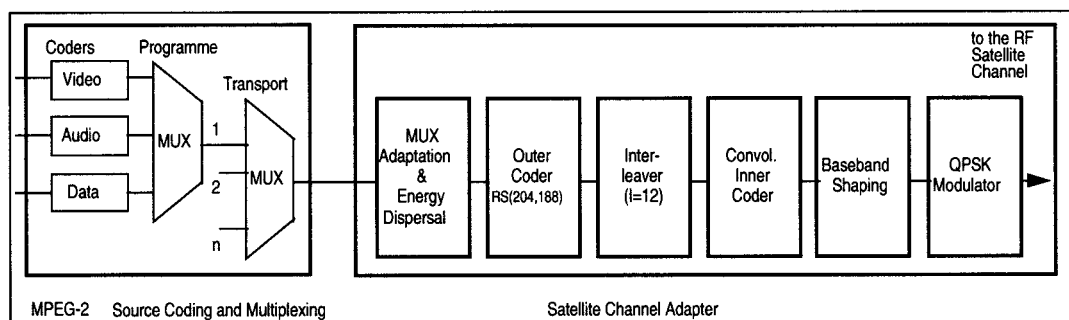


Figure 2. The DVB-S system for satellite digital television.

2.1. Source coding and multiplexing

Over the last 10 years, sophisticated bit-rate reduction algorithms, such as Hybrid DCT with motion compensation, have been implemented in VLSI circuits, which form the basis of flexible and efficient TV/HDTV source codecs. For broadcasting and consumer TV applications the MPEG-2 standard has been established by ISO/IEC in 1993. The DVB Project has chosen the MPEG-2 (main profile at main level (MP@ML)), image coding algorithm, operating with 50 Hz field rate (interlaced) with 4:3 or 16:9 aspect ratios. Subjective quality assessments show that, starting from a 4:2:2 video source, an average picture quality comparable to PAL is achievable at about 4–6 Mbit/s (e.g. SDTV), while a quality subjectively equivalent to that available in the studio, according to ITU-R Rec. 601, requires about 8–9 Mbit/s (EDTV quality). The adoption of other MPEG-2 profiles and levels potentially allows for compatible future evolution towards HDTV, at bit rates in the range from 15 to 30 Mbit/s. These figures refer to the video signals only; therefore, an additional capacity must be considered for sound channels, service information (SI), conditional access (CA) and additional data services (e.g. teletext, subtitling, multimedia services). The use of 'statistical multiplexing' may significantly increase (by a factor of 15–25 per cent) the number of programmes per multiplex, by dynamic bit-rate allocation between the various programmes, according to the instantaneous picture coding 'complexity'.

The DSNG links are by nature contribution links, the quality objectives of which are defined by Rec. ITU-R BT.1121. 'There is no need to define lower quality objectives, if it is understood that, due to circumstances, possible relaxations are to be accepted by the user. For DSNG links, the typical bit-rate used by fly-away and small transportable terminals is about 8 Mbit/s, using MPEG-2 MP@ML. However for transportable *stations*, when higher quality and enhanced editing facilities are required, 'the use of MPEG-2 422P@ML should be supported. In this case, bit-rates should be higher than 8 Mbit/s and lower than 34 Mbit/s'. The processing delays of digital compression systems may be very high (even exceeding one second), especially with the sophisticated coding algorithms allowing high bit-rate compression ratios. Short video coding delays are important characteristics for those applications where the DSNG transmission is mixed together with a live programme, since long delays would prevent dialogues between journalists in the studio and in the field.

The framing structure of the DVB-S and DVB-DSNG systems (Figure 3) is based on the adoption of MPEG-2 multiplex, which allows to merge, in a single transport stream, a large number of video, audio and data services. The transport packets have fixed length (188 bytes), including 1 sync byte, 3 header bytes (containing the packet identifiers, PID) and 184 useful bytes. No error protection is included on the packet headers, therefore a rugged '*channel adaption layer*' is required, capable of providing an error-free data stream to the demultiplexer.

The multiplex is highly flexible and carries a service information channel to assist the user in programme selection. For DSNG applications, a simplified SI structure has been defined, in order to allow rapid link set-up in the field. Regarding multiplexing, the DVB-CM indicated that '*although DSNG transmissions usually transport a single TV programme and associated sound signals single channel per carrier (SCPC), advantage should be taken of the flexibility of the MPEG-DVB multiplex to convey multiple programmes' multiple channels per carrier (MCPC)*'.

2.2. Channel coding and modulation

The channel coding and modulation scheme performs the adaptation to the satellite channel of the baseband TV signals at the output of the MPEG-2 transport multiplexer.

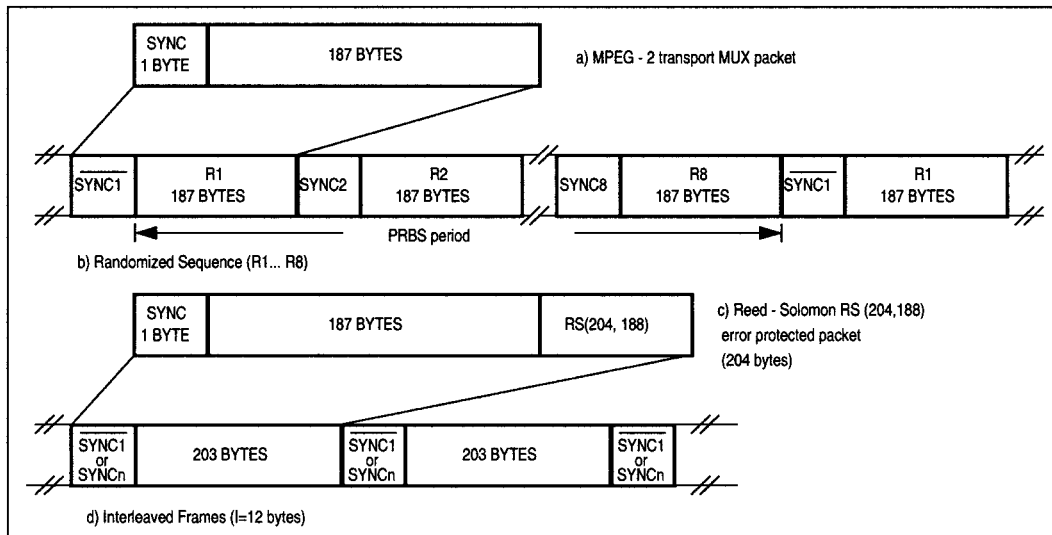


Figure 3. Multiplexing and transmission structure.

The transmission performance of a digital system by satellite depends on the various components included in the chain:

- (a) transmit earth station;
- (b) space segment (up-link U/L and down-links D/L);
- (c) satellite transponder (IMUX and OMUX filters, TWT amplifier);
- (d) receive earth station.

The satellite channel is basically *non-linear*, *wide-band* and *power limited*. The main signal impairments are introduced by noise, rain attenuation and interference on the space segment and by incorrect alignment of transmit and receive stations and equipment. The non-linearity (amplitude and phase distortions) of the on-board travelling wave tube amplifier (TWTA) is responsible for impairments on the overall system performance.

In the case of digital DTH services addressed to the general public, a single carrier is transmitted in the transponder and, to achieve the maximum power efficiency, the satellite TWTA is usually operated close to saturation. The effects of TWTA non-linearity are waveform distortion and side-lobe regeneration of the power spectrum. In these applications, due to the reduced dimensions of the receiving antennas, the service availability is mainly limited by the down-link noise.

For DSNG and contribution applications the usual method of accessing the transponder is frequency division multiplexing (FDM), where part of the transponder bandwidth (frequency slot) is allocated to each signal, in SCPC mode. In order to reduce the effect of intermodulation noise introduced on adjacent carriers occupying the same transponder, the TWTA must be operated significantly below the saturation point. The linearity requirements are raised also by the fact that the aggregated FDM signal is no longer characterized by a constant envelope, even if each individual signal has quasi-constant envelope (e.g. QPSK or 8PSK). The higher is the spectrum

efficiency of the modulation/coding scheme, the more stringent are the linearity requirements, because of the reduction of the system ruggedness against intermodulation interference from the adjacent signals.

Efficient and reliable transmission of digital television signals over satellite channels is focused on the design of the 'channel adapter', which performs the adaptation of the multiplexed video/audio/data bit stream to the physical channel, by adopting powerful channel coding and modulation techniques. In the definition of the DVB systems, the design target has been the minimization of the effects of the various channel impairments, such as additive noise, interference from analogue and digital signals, linear and non-linear distortion. The specified system offers many transmission modes (inner coding and modulations), giving different trade-offs between power and spectrum efficiency. QPSK modulation and the concatenation of convolutional and Reed-Solomon codes have been adopted for the DVB-S system, in order to cope with the power limitations and the severe non-linear distortions which are typical of DTH applications. The convolutional code is able to be configured flexibly at different rates allowing the optimization of the system performance for a given satellite transponder bandwidth. Coherent demodulation and soft-decision Viterbi decoding are used in the receiver.

The 'professional' DVB-DSNG system, in addition to the QPSK mode of the DVB-S system, optionally includes 8PSK and 16QAM modulations, in order to cope with higher spectrum efficiency requirements, but at the cost of a reduced immunity against interference and noise.

The QPSK and 8PSK modes, to their quasi-constant envelope, are appropriate for operation with saturated satellite power amplifiers, in single carrier per transponder configuration. 16QAM (as well as QPSK and 8PSK) is appropriate for operation in quasi-linear satellite channels, in multi-carrier frequency division multiplex (FDM) type applications, with better spectrum efficiency.

The transmission frame (Figure 3(a)) is synchronous with the MPEG-2 transport multiplex. In order to comply with radio regulations for spectrum occupancy and to facilitate clock-recovery in the receiver, the data at the output of the MPEG-2 multiplexer are bit-by-bit randomized. The scrambling pseudo-random binary sequence (PRBS) is synchronized to a frame of eight MPEG-2 packets (Figure 3(b)), delimited by two inverted MPEG-2 sync bytes (SYNC 1), which are not scrambled. The randomized packets are encoded by the Reed-Solomon code RS(204, 188), which is a shortened version of the original RS(255, 239). The code adds 16 redundancy bytes to the 188 bytes of the randomized packets (Figure 3(c)), and provides correcting capability of $T = 8$ random byte-errors.

In the concatenated coding scheme adopted in the system, the errors at the output of the Viterbi decoder are not statistically independent, but are instead grouped in bursts which may overload the RS code. To improve the burst-error correcting capability of the RS code, convolutional interleaving, with depth $I = 12$ at byte level, is applied to the error-protected packets (Figure 3(d)).

The interleaving scheme is based on the Forney approach (Figure 4), and is composed of 12 first-in-first-out memory elements in parallel, with different lengths (from 0 to 11×17 bytes). The obtained interleaved frame is composed of overlapping error protected packets and is delimited by MPEG-2 sync bytes (preserving the periodicity of 204 bytes). For synchronization purposes, the sync bytes are always routed in the branch '0' of the interleaver and of the de-interleaver.

The interleaved frame is encoded by a convolutional punctured code, with constraint length $K = 7$, which can operate at five possible rates: $\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{5}{6}$ or $\frac{7}{8}$, selectable in accordance with the service requirements.

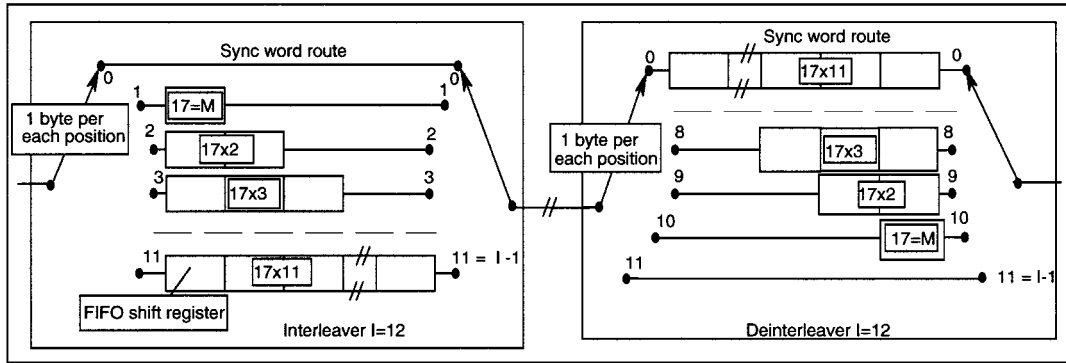


Figure 4. Conceptual diagram of the convolutional interleaver and de-interleaver.

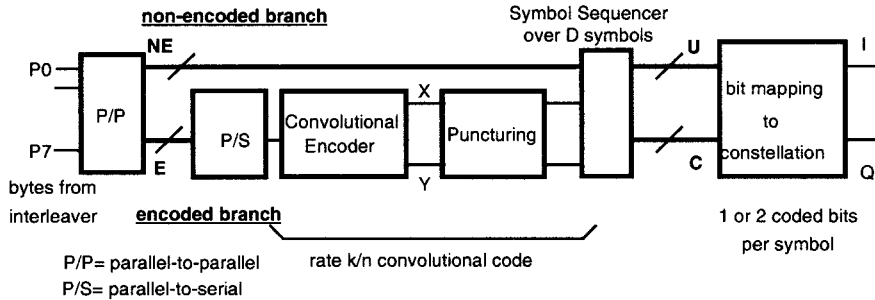


Figure 5. Inner trellis coder principle.

In the DVB-DSNG system, ‘pragmatic’ trellis coded modulations (TCM) [6] are associated with 8PSK and 16QAM. A principle scheme of the pragmatic trellis encoder is shown in Figure 5. The byte-parallel stream at the output of the convolutional interleaver is conveyed to a parallel-to-parallel converter, which splits the input bits into two branches, depending on the selected modulation/inner coding mode.

The signals NE of the non-encoded branch generate, through the symbol sequencer, a sequence of signals U, each to be transmitted in a modulated symbol. These bits generate parallel transitions in the trellis code, and are only protected by a large Euclidean distance in the signal space. The signal E in the encoded branch is processed by the punctured convolutional encoder. These bits generate, through the symbol sequencer, a sequence of signals C, each to be transmitted in a modulated symbol. The 8PSK $\frac{5}{6}$ and $\frac{8}{8}$ schemes are characterized by one coded bit per symbol (1CBPS), while 8PSK $\frac{2}{3}$ and 16QAM $\frac{3}{4}$ and $\frac{7}{8}$ schemes have two coded bits per symbol (2CBPS). Optimum bit mapping to constellation is different for 1CBPS and 2CBPS. The selection of the trellis coding schemes, from a number of different proposals, was based on accurate computer simulations carried out by the RAI Research Centre. The selected schemes are the ones offering the best performance on a linear channel affected by additive white Gaussian noise (AWGN). In the cases of equal performance 1CBPS schemes have been preferred, since they require lower processing speed of the Viterbi decoder compared to 2CBPS schemes, and therefore

allows the implementation of higher speed modems (for high-quality contribution applications or MCPC transmissions).

Finally, the coded bits are mapped in the QPSK, 8PSK or 16QAM constellations and filtered at baseband to generate a square-root raised cosine spectrum, with roll-off $\alpha = 0.35$. An additional roll-off factor $\alpha = 0.25$ may be used for the 8PSK and 16QAM modulations, to increase the spectrum efficiency in the transponder bandwidth. This choice was based on extensive computer simulations, including the satellite TWTA effects.

3. SYSTEM FLEXIBILITY AND PERFORMANCE

3.1. Bit-rate capacity vs transponder bandwidth

One of the main features of the DVB satellite systems is the flexibility, allowing to select the modulation, the symbol rate and the coding rate in order to optimize the satellite link performance (i.e. the spectral occupation on the satellite transponder and the power requirements) on a case-by-case basis.

In single-carrier per transponder configurations (typical for the broadcasting applications), the transmission symbol rate R_S can be matched to a given transponder bandwidth BW (at -3 dB, combination of IMUX and OMUX filters), to achieve the maximum transmission capacity compatible with the acceptable signal degradation due to transponder bandwidth limitations. The transponder bandwidths of satellites currently into operation in Europe in the BSS and FSS bands range from 26 to 72 MHz; 33 MHz is typical for DTH applications.

The ratio BW/R_S determines the symbol rate transmitted in the satellite transponder for any particular bandwidth. Decreasing BW/R_S means that the symbol rate is increased and therefore the capacity available to transmit programmes. However, there is a BW/R_S lower limit caused by the acceptable distortion (inter symbol interferences, (ISI)), introduced by the satellite filters. The problem of choosing an optimum BW/R_S value is equivalent to estimating what is acceptable as a C/N degradation compared to the gain in symbol rate and useful bit-rate.

Figure 6 (taken from Reference [2] and based on RAI simulations) gives an example of the E_b/N_0 degradation at $BER = 2 \times 10^{-4}$ on the computer-simulated satellite channel due to bandwidth limitations (IMUX and OMUX). $BER = 2 \times 10^{-4}$ (after Viterbi decoding) is adopted as a reference for DVB systems, and is often indicated as 'quasi-error-free (QEF) target, since it corresponds to less than one uncorrected error per transmission hour after Reed-Solomon decoding. The reference 0 dB degradation refers to the case of a satellite transponder without bandwidth limitations ($BW = \infty$), and with saturated TWTA ($OBO = 0$ dB). The inner coding rates $\frac{2}{3}$ and $\frac{7}{8}$, associated with uncoded QPSK modulation, have been analysed. When using the results of Figure 6, suitable margins should be allowed to take into account thermal and ageing instabilities of the transponder characteristics.

In multi-carrier FDM configuration, R_S can be matched to the frequency slot BS allocated to the service by the frequency plan, to optimize the transmission capacity while keeping the mutual interference between adjacent carriers at an acceptable level.

Figure 7 gives examples of the maximum useful bit rate capacity R_u achievable by the DVB-S and DVB-DSNG systems vs the allocated bandwidths BW or BS. R_u stands for the useful bit rate (188 byte format) after MPEG-2 MUX. R_S (symbol rate) corresponds to the -3 dB bandwidth of the modulated signal. $R_S(1 + \alpha)$ corresponds to the theoretical total signal bandwidth after the

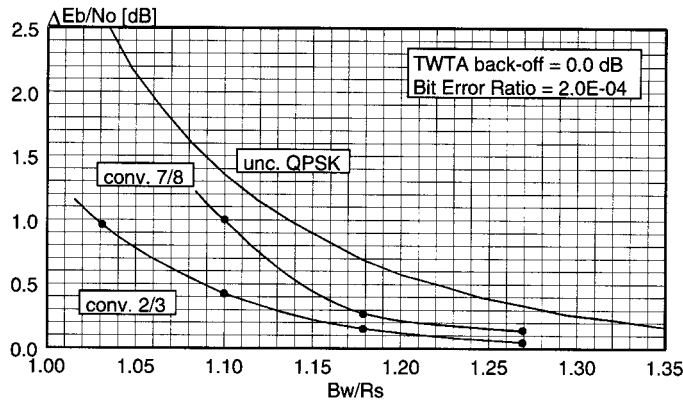


Figure 6. E_b/N_0 degradations due to transponder bandwidth (BW) limitations.

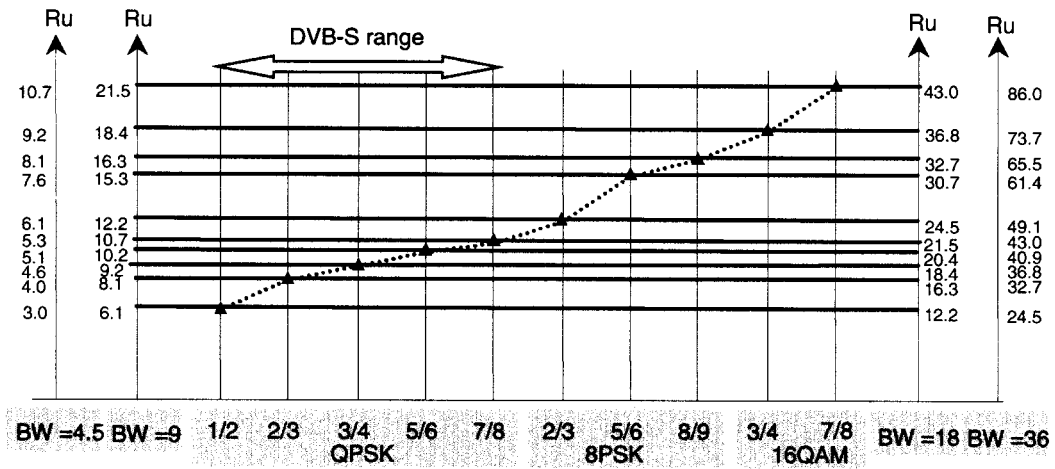


Figure 7. Bit rate capacity vs available bandwidth.

modulator. The figures for very low and very high bit-rates may be irrelevant for specific applications. In these examples the adopted BW/R_s or BS/R_s ratios are $\eta = 1 + \alpha = 1.35$ where α is the roll-off factor of the modulation. This choice allows the obtaining of a negligible E_b/N_0 degradation due to transponder bandwidth limitations (see Figure 6 to QPSK), and also to adjacent-channel interference on a linear channel. Higher bit-rates can be achieved with the narrow roll-off factor $\alpha = 0.25$ (optional for 8PSK and 16QAM) and BW/R_s or BS/R_s equal to $\eta = 1 + \alpha = 1.25$.

BW/R_s or BS/R_s ratios different from $1 + \alpha$ may be adopted for different service requirements. The adoption of figures significantly lower than $1 + \alpha$ (e.g. $BS/R_s = 1.20$ associated with $\alpha = 0.35$), to improve the spectrum exploitation by slightly overlapping the modulated signals in the frequency domain, should be carefully studied on a case-by-case basis, since severe performance degradations may arise due to bandwidth limitations and/or adjacent channel interference, especially with 8PSK and 16QAM modulations and high coding rates (e.g. $\frac{5}{6}$ or $\frac{7}{8}$).

3.2. E_b/N_0 vs BER

Sensitivity to transmission noise is expressed, for the various rates of the convolutional code, by the E_b/N_0 ratio required to achieve a target residual BER. E_b is the energy per useful bit and N_0 is the spectral density of the AWGN. DVB systems have been designed to provide a quasi-error free quality target, i.e., approximately less than one incorrect error-event per transmission hour at the input of the MPEG-2 demultiplexer. This target, achievable by interleaving and by RS error correction, corresponds to a bit error ratio (BER) of about 2×10^{-4} at the output of the TCM/Viterbi decoder and to a byte error ratio between 7×10^{-4} and 2×10^{-3} depending on the coding scheme. It should be noted that these evaluations take into account stationary noise only and ideal demodulation, while the effects of phase noise and carrier recovery instabilities might generate a burst of uncorrectable errors separated by large time intervals. Since the DVB-DSNG coding schemes are not rotationally invariant (to optimize the BER performance), care should be taken in the design of frequency converters and carrier recovery systems, to avoid 'cycle skipping' and 'phase snaps', which may produce service interruptions.

Table I gives the IF-loop system performance requirements for the different modes, in terms of the required E_b/N_0 to provide BER = 2×10^{-4} (quasi-error-free quality target). The figures of E_b/N_0 refer to the useful bit-rate R_u (188 byte format, before RS coding), and take into account the factor $10 \log \frac{188}{204} \cong 0.36$ dB due to the Reed–Solomon outer code and the modem implementation margins reported in the fifth column. For 8PSK and 16QAM, modem implementation margins which increase with the spectrum efficiency are adopted, to cope with the larger sensitivity associated with these schemes. 8PSK $\frac{8}{9}$ because of its quasi-constant envelope, is suitable for satellite transponders driven near saturation, while 16QAM $\frac{3}{4}$ offers better spectrum efficiency for quasi-linear transponders, in FDMA configuration.

The ruggedness against noise of digital TV (QPSK- $\frac{3}{4}$) and analogue PAL/FM on the satellite channel are shown in Figure 8. The quality impairment is expressed in terms of the required signal-to-noise power ratio C/N, assuming as reference an analogue receiver bandwidth B_{RX} of 36 MHz, which is typical of satellite FM/TV transmissions with 25 MHz/V frequency deviation. To perform a fair comparison, the digital system is operated in 'single signal per

Table I. IF-loop performance of the DVB satellite systems.

System	Modulation	Inner code rate	Spectral efficiency (bit/symbol)	Modem implement margin (dB)	Required E_b/N_0 (dB) for BER = 2×10^{-4} before R_s
DVB-S & DVB-DSNG	QPSK	$\frac{1}{2}$	0.92	0.8	4.5
		$\frac{2}{3}$	1.23	0.8	5.0
		$\frac{3}{4}$	1.38	0.8	5.5
		$\frac{5}{6}$	1.53	0.8	6.0
		$\frac{7}{8}$	1.61	0.8	6.4
DVB-DSNG (optional)	8PSK	$\frac{2}{3}$	1.84	1.0	6.9
		$\frac{5}{6}$	2.30	1.4	8.9
		$\frac{8}{9}$	2.46	1.5	9.4
DVB-DSNG (optional)	16QAM	$\frac{3}{4}$	2.76	1.5	9.0
		$\frac{7}{8}$	3.22	2.1	10.7

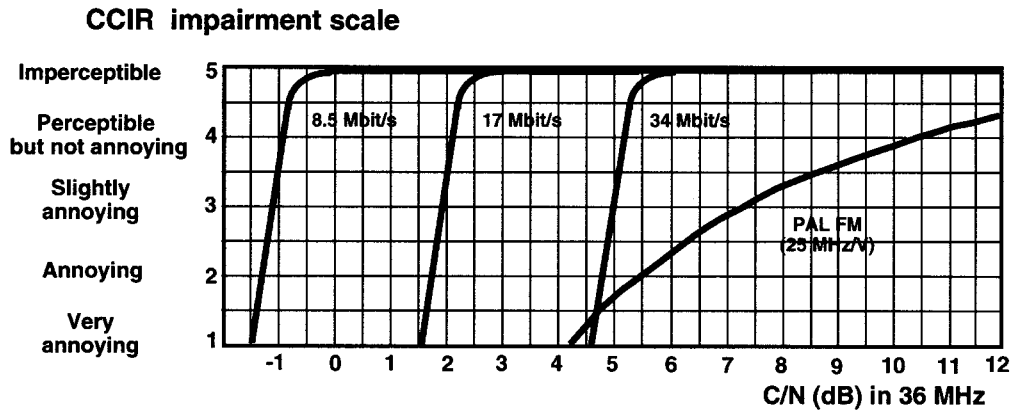


Figure 8. Picture impairment vs C/N: digital TV (QPSK- $\frac{3}{4}$) and analogue FM/TV on a satellite channel.

transponder' configuration, and the C/N ratio is measured in the same bandwidth B_{RX} of 36 MHz as the analogue signal (about 1 dB additional degradation on the transponder should be considered).

From Figure 8 a DSNG signal at 17 Mbit/s, providing near-contribution quality, would require about 3 dB C/N (in 36 MHz) to operate quasi-error-free against 12–13 dB required by analogue FM/PAL for an acceptable picture quality. If the transmission rate is reduced to 8.5 Mbit/s, which is suitable for DSNG applications with PAL quality, the required C/N ratio would approach 0 dB.

Thanks to this remarkable performance the digital solution is then able to virtually deliver the picture and sound quality of the 'compressed' source, provided that an adequate margin against rain attenuation is allowed by careful link budget design in order to operate above the service continuity threshold.

The DVB systems have a very steep failure characteristic (about 0.9 of C/N variation to pass from QEF to service outage). So the satellite power design should not be based on the conventional criteria used for TV/FM services (e.g. quality grade = 3.5 of the CCIR 5-level quality scale for 99 percent of the worst month at the coverage area contours), but on extended service continuity targets (e.g. more than 99.6 percent of the worst month, corresponding to about 99.9 percent of the average year). Assuming a typical propagation condition at 12 GHz in Europe (i.e. climatic zone K), a C/N margin of about 2 dB is required to extend the service continuity from 99 to 99.7 percent of the worst month. This margin should be taken into account also when comparing analogue and digital systems.

4. ANTENNA SIZE VERSUS BIT-RATE AND TRANSPONDER BANDWIDTH

4.1. DTH applications (DVB-S)

Table II highlights the impact on the usable bit-rate (R_u) and inner code-rate, in the range $\frac{1}{2}$ – $\frac{7}{8}$, on the antenna size required at 12 GHz for 99.9 percent (average year) service availability (*quasi-error-free* quality), in climatic zone E (in Europe). The main link-budget assumptions are: antenna

Table II. Antenna size, bit-rate R_u and transponder bandwidth (BW) for DTH applications.

BW at -3 dB (MHz)	Symbol rate R_s (Mbaud)	FEC = $\frac{1}{2}$		FEC = $\frac{2}{3}$		FEC = $\frac{3}{4}$		FEC = $\frac{5}{6}$		FEC = $\frac{7}{8}$	
		R_u (Mb/s)	Diam. (m)	R_u (Mb/s)	Diam. (m)	R_u (Mb/s)	Diam. (m)	R_u (Mb/s)	Diam. (m)	R_u (Mb/s)	Diam. (m)
54.0	42.2	38.9	0.47	51.8	0.58	58.3	0.65	64.8	0.72	68.0	0.77
46.0	35.9	33.1	0.43	44.2	0.53	49.7	0.60	55.2	0.67	58.0	0.72
40.0	31.5	28.8	0.41	38.4	0.50	43.2	0.56	48.0	0.62	50.4	0.67
36.0	28.1	25.9	0.38	34.6	0.47	38.9	0.53	43.2	0.59	45.4	0.63
33.0	25.8	23.8	0.37	31.7	0.45	35.6	0.51	39.6	0.56	41.6	0.61
30.0	23.4	21.6	0.35	28.8	0.43	32.4	0.48	36.0	0.54	37.8	0.58
27.0	21.1	19.4	0.33	25.9	0.41	29.2	0.46	32.4	0.51	34.0	0.55
26.0	20.3	18.7	0.32	25.0	0.40	28.1	0.45	31.2	0.50	32.8	0.53

Note: Satellite EIRP: 51 dBW; service availability: 99.90 percent average year (a.y.) in climatic zone 'E' in Europe; R_u = usable data rate at the input of MPEG-2 Transport De-Multiplexer.

pointing losses 0.5 dB, external interference 1 dB, antenna efficiency 70 per cent, antenna noise temperature 35 K, coupling losses 0.2 dB, satellite and modem degradation 1.8 dB, up-link contribution 0.2 dB, satellite EIRP 51 dBW.

The link budget hypothesis has been made taking into account the performance of current TVRO domestic receivers (LNB noise figure of 1.1 dB).

From Table II it can be understood that, under the above assumptions, a receiving antenna size of the order of 60 cm would allow the use of 41.6 Mbit/s, for FEC $\frac{7}{8}$, with a transponder bandwidth of 33 MHz. The usable bit-rate for any other combination of FEC rate, transponder bandwidth and receiving antenna can be directly derived from Table II.

4.2. Contribution applications (DVB-DSNG)

Link budget evaluations have been carried out to estimate the earth station characteristics required to achieve a suitable service continuity target (i.e. 99.9 percent or 99.6 percent of the average year) in Italy, on a typical Ku-band satellite with European-wide up-link and down-link coverage. Two Italian up-link locations have been chosen representing a typical case (Palermo, ITU climatic zone K), and a worst case (Turin, ITU climatic zone L) in the European scenario, while reception has been assumed in Rome (climatic zone K). To allow a fair comparison of the results, the link budgets have been optimized in each location, although it is clear that operation in Italy would require the adoption of a uniform set of transmission parameters, such as the satellite transponder gain setting. For DSNG applications, the up-link antenna diameters have been minimized, while neglecting the possibility to receive the transmitted TV signal by the DSNG terminal. For contribution links connecting fixed stations, the same antenna diameters have been adopted at the transmitting and receiving sites, in order to allow bi-directional exchange of programme material.

The following link characteristics have been considered:

Up-link terminal: Location: Turin (ITU climatic zone L), Palermo (ITU climatic zone K); frequency: 14.29 GHz; antenna efficiency: 60 percent; coupling loss: 0.3 dB; pointing loss: 0.3 dB; OBO: 2 dB for QPSK and 8PSK, 6 dB for 16QAM.

Up-link propagation: Atmospheric loss and rain attenuation:

- (a) for 99.9 percent of average year (a.y.): 0.2 + 5.6 dB (Turin), 0.1 + 3.9 dB (Palermo),
- (b) for 99.6 percent of average year (a.y.): 0.2 + 2.9 dB (Turin), 0.1 + 2.0 dB (Palermo).

Satellite: G/T (dB/K): 4.3 (Turin), 3.6 (Palermo); IPFD for saturation (from -0.5 dB/K contour): variable (-80 dBW/m² nominal gain setting); transmitted EIRP at saturation: 46.5 dBW (to Rome).

Down-link propagation: Atmospheric loss and rain attenuation (Rome):

- (a) for 99 percent a.y.: 0.1 + 2.4 dB,
- (b) for 99.6 percent a.y.: 0.1 + 1.2 dB.

Receiving station: Location: Rome (zone K); frequency: 10.99 GHz; antenna efficiency: 60 percent; coupling loss: 0.5 dB, pointing loss: 0.5 dB; LNB noise figure: 1.1 dB.

The link analysis method is based on the figures of Table I (IF-loop performance) and on computer simulations to estimate the noise margin losses due to the non-linearity, the input/output signal power levels and the intermodulation interferences (C/I) between signals, following a simplified analysis method. An additional link margin of 1 dB has been introduced, in order to cope with possible inaccuracies of the analysis method. The link budgets have been balanced to achieve the target service continuity (99.9 per cent or 99.6 per cent of the average year) under up-link fading; subsequently, the availability of positive margins has been verified under down-link fading (for the same service continuity target).

Table III shows the results of this analysis for a 36 MHz transponder.

From the examples of Table III, the following considerations may be drawn. For DSNG applications, four QPSK $\frac{3}{4}$ signals at 8 Mbit/s may be placed in a 36 MHz transponder (9 MHz frequency slots, see the first row in Table III). In this configuration, very small *fly-away* up-link terminals may be used, with EIRP in the range 56–59 dBW, and using 3 m receiving antennas. When higher picture quality is needed, such as MPEG-2 422P@ML at bit-rates of 21.5 Mbits/s, while keeping small the DSNG up-link terminal antenna (1.5 m), the satellite bandwidth exploitation has to be reduced from four to two FDM signals (see row 2 in Table III). This configuration requires a larger receiving antenna (4 m). Using 8PSK $\frac{5}{6}$ signals (see rows 3 and 4 in Table III), three to four carriers may share the satellite transponder, offering bit-rates of about 20 and 15 Mbit/s, respectively. These configurations require large vehicle-mounted DSNG stations (2.4 m antenna diameter) and large receiving antennas (6 m diameter). Significantly better results, in terms of requested antenna diameters, may be obtained using satellites with smaller up-link coverage (e.g. national instead of Pan-European), since the higher satellite G/T directly improves the up-link performance.

For fixed contribution links, high bit-rates (MPEG-2 422P@ML video) and high spectrum efficiencies are often required. In the examples of Table III (rows 5 and 6), four 16QAM signals at 18.4 or at 21.5 Mbit/s are allocated in 9 MHz frequency slots, using large transmitting and receiving stations (6 to 8 m antennas). At 21.5 Mbit/s, due to the high C/N + I requirements of 16QAM rate $\frac{7}{8}$, a slightly reduced service availability is accepted to keep the antenna diameters at an acceptable level.

It should be noted that in typical operational environments the optimization of the transponder gain setting (see 'IPFD at saturation' in Table III) is limited to about ± 3 dB with respect to the *nominal* gain setting, in order to keep balanced the up-link power levels in

Table III. Example use of the system for DSNG and fixed contribution applications N digital signals in FDMA in a 36 MHz transponder.

Signals		UP-link terminal						Satellite		RX station	
Useful bit-rate (Mbit/s)	Modul. & coding	Target service availability* (%)	Type	ITU climate zone	HPA power† (W)	Antenna diameter (m)	EIRP‡ (dBW)	IPFD§ (dBW/m)	IBO¶ per carrier (dB)	OBO¶ total (dB)	Antenna diameter (m)
1	8.448 QPSK $\frac{3}{4}$	99.9	DSNG flyaway	L K	110 70	0.9	58.5 56.5	-84 -87	15.7 15.2	4.2 3.9	3
2	21.50 QPSK $\frac{7}{8}$	99.9	DSNG vehicle	L K	100 70	1.5	62.5 61.0	-82 -86	13.7 11.8	3.7 2.7	4
3	20.48 8PSK $\frac{5}{6}$	99.9	DSNG vehicle	L K	230 90	2.4	70.2 66.1	-70 -74	18.0 18.6	6.6 7.1	6
4	15.357 8PSK $\frac{5}{6}$	99.9	DSNG vehicle	L K	300 75	2.4	71.4 65.3	-68 -74	18.9 19.4	6.8 7.2	6
5	18.43 16QAM $\frac{3}{4}$	99.9	Fixed contribution	L K	250 60	7 6	75.9 68.3	-62 -71	20.4 19.4	8.0 7.3	7 6
6	21.50 16QAM $\frac{7}{8}$	99.6	Fixed contribution	L K	60 70	8 7	70.8 70.3	-67 -68	20.4 20.4	8.1 8.1	8 7

* Percentage of the average year; up-link fading.

† At saturation.

‡ At OBO = 2 dB (QPSK and 8PSK), 6 dB (16QAM).

§ IPFD for up-links on the -0.5 dB/K contour.

¶ Nominal in clear sky.

cross-polar transponders and avoid severe interference problems on the up-link. Nevertheless, in the given examples a significantly wider adaptation has been allowed (in the range $+7 - 19$ dB), requiring careful interference handling by the satellite operator. This is necessary with high-level modulations, demanding both high $C/N + I$ ratios on the up-link and good transponder linearity.

5. COMMONALITY WITH CATV/SMATV

Satellite television broadcasting, although primarily focused on direct-to-home reception, requires signal distribution via the large cable networks (CATV), serving thousands of users, and community receiving installations (satellite master antenna TV, SMATV) serving single buildings, with a roof-top satellite receiving antenna.

In Europe, the characteristics and performance of CATV and SMATV networks are quite different. CATV networks are professionally implemented in accordance with the CENELEC 50083-7 standard and are monitored by technical operators and fulfill precise distortion requirements. Conversely, SMATV networks are domestic TV systems using low-cost consumer technology and simple design methods, without a regular performance control. This implies that the technical quality, particularly in old installations, can be significantly lower than that achievable via CATV networks.

Moreover, different needs arise for large CATV installations, which can afford expensive processing at the cable head-end (e.g. demodulation, multiplex processing to drop-insert programmes, re-modulation) and SMATV installations where the additional cost of upgrading the head-end unit must be kept as low as possible.

The adoption of a unique modulation scheme optimized for satellite and cable is practically impossible. In fact, the satellite channel is basically non-linear and power-limited, but it does not suffer from stringent bandwidth limitations, whereas cable channels are linear and allow relatively high S/N ratios, but they are band-limited and currently affected by echoes and other distortions.

The modulation and channel coding system for use on CATV networks has been defined within the DVB project [4]. In order to allow maximum transparency and receiver commonality the same baseband processing (randomization, Reed-Solomon coding, interleaving) of the satellite system has been adopted. However, high-level quadrature modulations, i.e. 16 QAM, 32 QAM or 64 QAM, with 15 percent roll-off, have been introduced to allow transport of typical satellite bit-rates on 8 MHz cable channels. To increase spectrum efficiency the convolutional inner code is not adopted; thus, a usable bit-rate of about 38 Mbit/s; at the MPEG multiplexer output, is made available with 64 QAM modulation, at a symbol rate R_s of about 7 Mbaud.

Table IV shows the two DVB approaches for distribution of digital TV signals in SMATV installations, the first based on the DVB-S system, the second on the DVB-C system.

Computer simulations and laboratory tests have demonstrated that adaptive equalization is necessary with method B to overcome typical linear distortions of current SMATV networks (Figure 9).

6. CONCLUSIONS

The DVB-S system for satellite broadcasting of multi-programme digital television, developed within the DVB project with the significant support of the EBU and the co-operation of service

Table IV. Digital television distribution in SMATV networks.

Method	A	B
DVB system	DVB-S frequency conversion only	DVB-C trans-modulation from DVB-S
Band (MHz)	<i>L</i> -band (satellite front-end IF): 950–2050 (new installations)	VHF/UHF (7–8 MHz channels) (sharing with analogue TV)
Band (MHz) channel capacity	extended superband: 230–470 7 channels with 33 MHz spacing	extended superband: 230–470 30 channels with 8 MHz spacing

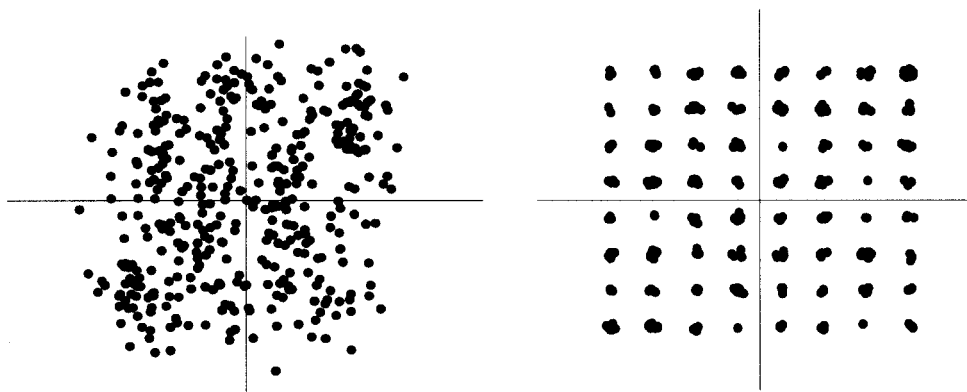


Figure 9. Typical constellation diagram in SMATV installations, before and after equalization.

providers, satellite and cable operators and the consumer electronics industry, is becoming a de-facto world-wide standard, excluding few exceptions. The system allows short-term introduction of direct-to-home digital television services via satellite channels in the FSS and BSS bands with different TV service configurations as suggested by the market demand.

The inherent system flexibility allows the establishment of a trade-off between transmission capacity (i.e. number of TV programmes per satellite transponder) and power requirements (i.e. satellite EIRP and receiving antenna diameter). Depending on the transponder bandwidth (for example from 26 to 54 MHz) and on the level of error protection by convolutional coding (rate $\frac{1}{2}-\frac{7}{8}$) usable data rates from 18.7 to 68 Mbit/s can be transmitted, taking also into account the required receiving antenna diameter.

For distribution of the satellite signals in cable networks (CATV and SMATV) with 8 MHz channelling, remodulation from QPSK to QAM (16, 32 or 64) is necessary. Alternatively, QPSK modulation may be maintained in SMATV.

The DVB-DSNG system offers significant advantages in terms of picture quality (MPEG-2 coding with 4:2:0 and 4:2:2 image format), modulation/coding flexibility and rapid link setup for DSNG applications. For example, on a typical Pan-European satellite one to four digital TV signals may be allocated in a 36 MHz bandwidth transponder, in frequency division multiplex (FDM). The link budget results indicate that, using QPSK modulation, DSNG services at 8 Mbit/s may be established with small 'fly-away' terminals using 0.9 m antenna diameters. When

higher picture quality is required (e.g. from 15 to 21 Mbit/s), using QPSK or 8PSK modulations, DSNG services may be established by vehicle-mounted terminals (1.5–2.4 m antenna diameters). In the case of fixed contribution links at high bit-rates (e.g. 18–21 Mbit/s), 16QAM modulation may be chosen to increase the space segment exploitation, at the cost of an increased dimension of the transmitting/receiving antennas (e.g. from 6 to 8 m diameters).

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Mario Cominetti graduated in Physics from the University of Turin. He was Deputy Director at the RAI Research Centre until December 1999 and was involved in R & D activities on advanced digital broadcasting systems for television, radio, and multimedia services. In June 1990, on the occasion of the World Cup Football in Italy, he co-ordinated the first European experiment of distribution via satellite of digital HDTV carried out by the RAI in cooperation with Telettra. He was the Chairman of European Broadcasting Union (EBU) Sub-group V2 (Data Broadcasting) and is member of the EBU Broadcast Management Committee. As Special Rapporteur in the European digital video broadcasting (DVB) Consortium he led the studies for the definition of the transmission standard for direct-to-home digital television via satellite. Cominetti has published several technical articles and has given conference contributions on advanced digital system and broadcast multimedia. He was awarded

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