DIRECT SATELLITE TELEVISION BROADCASTING

Direct-to-home (DTH) satellite television broadcasting has no strict technical or legal definition. During the past two decades the term has been used to delineate commercial systems that deliver television directly to consumer homes using communications satellites in geosynchronous orbit. Systems originally intended for DTH applications have operated at downlink frequencies above 11 GHz and with antennas of 1 m or less. Certain systems operated at 4 GHz were planned for cable television distribution and became, secondarily, DTH systems with customer parabolic antennas in the 2.5 m to 3.0 m range. Most systems have been supported primarily from subscription and pay-per-view revenues rather than advertising revenues. In the various direct-to-home systems deployed worldwide, a variety of technologies has been used, including analog and digital modulations and both standard and high-definition television formats. Certain systems have been entirely national in scope, while others have broadcast on a regional basis. From a regulatory viewpoint, both Fixed Satellite Service (FSS) bands and Broadcasting Satellite Service (BSS) bands have been used. Direct-to-home systems are sometimes also referred to as Direct Broadcast Satellite or DBS systems. This article describes the broadcasting and reception systems of a typical digital DTH broadcasting system, but does not cover the substantial infrastructure necessary for customer service and billing. (See also the articles Television broadcast transmission standards, Digital television, and Digital audio broadcasting.)

EVOLUTION AND EXISTING SYSTEMS

Although DTH satellite television was a dream of satellite engineers since the early 1960s, little progress was made until the early 1980s. Satellite technology steadily improved in generating high-radio-frequency (RF) power levels, and ground electronics improved by the introduction of low-cost, low-noise microwave transistors. Through 1994 these early systems used analog frequency modulation.

During the 1980s in the Americas, the earliest major system was the Satellite Technology Corporation project in the United States. This plan intended to deliver five channels to each time zone with a dedicated satellite for each. The user terminals were to employ parabolic dishes of 85 cm diameter. This project was abandoned, primarily for economic reasons. Also, in the United States during the 1980s, home reception began of satellite transmissions intended for delivery to cable television systems. The transmissions were at C band in the frequency range 3.7 GHz to 4.2 GHz. These early home dishes were 2.5 m to 3.0 m in diameter and cost several thousands of dollars, but increased satellite power permitted new C-band home dishes to drop in size to about 1.5 m by the early 1990s. This United States C-band DTH marketplace peaked at about 3.9 million homes in 1994. In Japan the quasigovernment broadcaster NHK utilized satellite delivery to 45 cm dishes for both standard National Television Systems Committee (NTSC) and Multiple Sub-Nyquist Encoding (MUSE) high-definition television. By 1993 this service, called BS for Broadcasting Satellite, was received by 4.5 million homes. The inexpensive analog BS receivers also became a typical feature of new television sets for the Japanese marketplace. In Europe the early use of satellites was for delivery of state-owned television networks. In the early 1990s, the Astra satellites became a major vehicle for DTH delivery of private, commercial channels. Multiple television broadcasters utilized Astra, including British Sky Broadcasting (BSkyB), which was providing over 40 analog channels to 6.4 million homes at the end of 1997 (1). Other European satellites are also providing DTH services, including Eutelsat and Hispasat.

During 1994 the era of multichannel, all-digital DTH satellite delivery began with two systems in the United States, the Primestar® system owned by a consortium of cable firms, and a system operated primarily by DIRECTV, Inc., a unit of Hughes Electronics. The Primestar system used "medium-power" satellites and approximately 0.75 m to 1.0 m dishes; the DIRECTV broadcast used "high-power" satellites and 45 cm dishes. By late 1997 the Primestar system delivered more than 160 channels to nearly 2 million homes in the United States by year end 1997. The DIRECTV service delivered more than 175 channels to 3.3 million homes in the United States by year end 1997. In 1995 another DTH business using "high-power" satellites entered this marketplace; this new entrant, EchoStar, reached approximately 1 million homes by year end 1997. AlphaStar, a short-lived DTH service, acquired only about 51,000 subscribers in the United States before filing for bankruptcy in 1997. Elsewhere in the Americas, three DTH services to Latin America were initiated in the early 1990s. One of these ventures, Galaxy Latin America, began broadcast operations in June 1995. Galaxy Latin America is a joint venture of Hughes and major media firms from Mexico, Venezuela, and Brazil. (The general company information given above was found at the World Wide Web sites listed in the Reading List.)

In Japan in 1996, the joint venture PerfecTV started multichannel, all-digital broadcasting with approximately a half-million subscribers by year-end 1997 (2). This firm was joined in the marketplace by DIRECTV JAPAN in December 1997. A third entrant, Japan Sky Broadcasting (JSkyB), announced in 1997 that it would merge with the first broadcaster, PerfecTV. All three firms use a Japanese industry variant of the Digital Video Broadcasting (DVB) format, and all three use medium-power FSS satellites. Within Japan the category of service provided by these three competitors is called Digital Communications Satellite, or Digital CS, in contrast to the high-power Broadcasting Satellite or BS service by NHK.

By early 1998 in Europe there were plans underway to convert existing analog systems, for example, BSkyB in the United Kingdom, and to launch new digital satellite platforms. New digital satellite systems in operation include DF1 in Germany; Telepiu in Italy; Via Digital (Hispasat) and Canal Satellite in Spain; TPS, AB-sat, and Canal Satellite Numerique in France (3).

REFERENCE ARCHITECTURE

Figure 1 shows a simplified diagram of an all-digital multichannel satellite DTH system. Figure 2 shows the exterior of a typical DTH broadcasting site including four 13 m uplink antennas.

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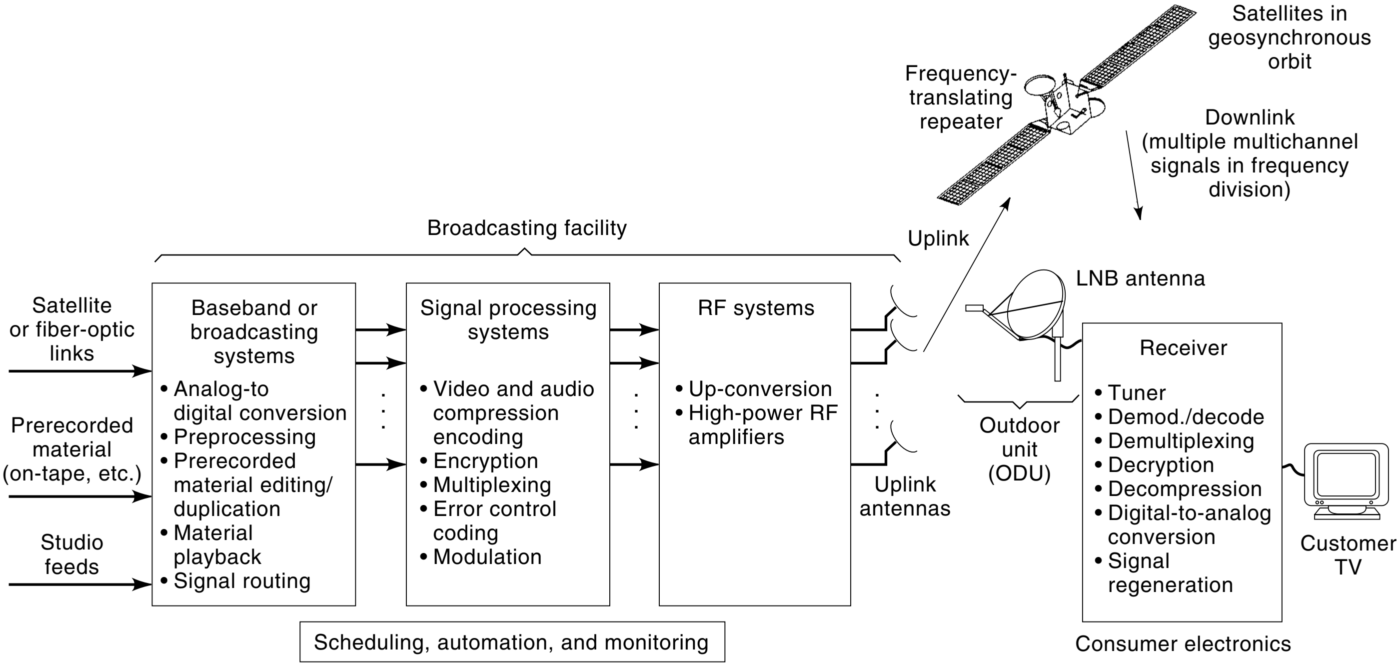

Figure 1. Simplified diagram of an all-digital multichannel satellite DTH system. Major broadcasting and transmission equipment groups are shown but not customer service and billing systems.

Broadcasting Facility

Most existing DTH systems have been used as delivery systems for existing programs, for example, broadening the market exposure of existing programming or delivering the programming with improved quality or convenience. As a delivery or rebroadcast system, a substantial portion of programming typically arrives at the DTH broadcasting or uplink facility via other “backhaul” satellites or terrestrial fiber. Programming, such as theatrical films, arrives at the facility as prerecorded digital tapes. In a limited number of systems, the broadcasting facility also includes studios for the creation of unique programming.

Figure 2. This DTH site in Colorado uses four 13 m antennas for uplink operations and numerous smaller dishes for programming reception. Courtesy of DIRECTV, Inc.

The broadcasting facility provides a number of functions common to any broadcasting facility, such as incoming signal monitoring, adjustment, and resynchronization, signal routing within the facility, and for prerecorded material, quality control, cloning, and playback. For playback, broadcast-quality tape players are utilized or, more recently, the material is stored on and played from video file servers using redundant arrays of independent disks (RAID) technology.

Large, multichannel “pay” DTH broadcasting also requires that the broadcast site provide *conditional access* equipment, service information/electronic program guide (SI/EPG) equipment, compression encoders, and multiplexing, error control, and modulation equipment. The conditional access system, which includes equipment within the home, permits customer access to programming services only when certain *conditions* have been met—for example, the customer account is in good standing or the customer is located outside a program blackout area. The SI/EPG equipment prepares specialized broadcast streams that provide the consumer equipment with technical attributes of each view channel (the service information), along with program content information for display by the home receivers. The EPG data typically include program title, start and stop time, synopsis, parental rating, etc. The signal compression equipment performs *redundancy reduction* processing on the television video and separately the audio to reduce the total information rate. A typical digital studio signal at 270 Mbit/s is reduced to the range of 2 Mbit/s to 10 Mbit/s before broadcast. This dynamically reduces the investment needed to put the transmission path in service (i.e., the satellites) and, conversely, greatly increases the number of available viewer channels for a given satellite investment. Most operational digital DTH systems have utilized the Motion Picture Experts Group (MPEG) 1 or MPEG 2 compression standards (4,5), or proprietary systems with similar characteristics. (See the section entitled "Compression.") The *compressed* streams from multiple channels are typically multiplexed into a single high-speed stream. This multiplexing process may be "fixed" in that peak bit rates are allocated to each video channel or, in certain systems, the individual channel rates may vary dynamically depending on their instantaneous bit-rate need—the latter approach is called *statistical multiplexing*. The composite bit stream is then coded by error control to add selective redundancy for error detection and correction. The error-control coding permits systems to be designed that offer high-quality operation with a lower threshold level than that possible in previous analog systems. The modulation utilized is commonly a constant envelope modulation such as quadrature phase shift keying (QPSK), which is typical of a satellite system for which the satellite repeater has a limiting final output stage.

Transmission Path

The transmission path includes the error-control coding and modulation described above, the uplink site's upconverters, transmitters, and antennas, the uplink propagation path, the relay satellite, and the downlink transmission path including the subscriber antenna and receiver front end. In all existing DTH systems, the satellite has been a frequency-translating microwave repeater. The expense of generating high satellite RF transmitter levels has caused these systems to be "downlink limited," meaning that the composite uplink and downlink carrier-to-noise ratio (CNR) is dominated by the downlink CNR. The downlink CNR is determined primarily by the satellite effective isotropic radiated power (EIRP) per transponder, carrier attenuation by rain along the line of sight, and the subscriber antenna gain. The subscriber electronics equipment completing the transmission path consists of a small aperture antenna, a low-noise block downconverter, tuner, demodulator, and error-control decoder. The "error corrected" information stream out of the error-control decoder is passed to the remainder of the digital circuitry within the receiver. (See the section entitled "Transmission.")

Home Electronics

The home electronics in a typical all-digital system include the antenna, low-noise block (LNB) converter, tuner–demodulator–decoder circuitry and other digital circuitry for demultiplexing, decryption under conditional access control, video and audio decompression, and video and audio output signal generation. For example, in digital receivers for the United States marketplace the final output circuitry recreates an analog composite NTSC or S-video signal for delivery to a standard television set. In a typical digital satellite receiver, a removable device, often in the form of an International Organization for Standardization (ISO) smart card, provides the conditional access control function. (See the section entitled "Consumer Electronics.")

THEORETICAL MODELS

Information Theory

Figure 3 shows a theoretical model useful in DTH system design, and the corresponding system elements used to implement the theoretical model. A text such as Ref. 6 describes an "ultimate" system design in which *source encoding* is used to remove redundancy information in the bit stream representing the source, that is, the television signal, and then *channel encoding* to protect the encoded source by carefully adding redundancy. Information theory tells us that source codes exist that can drive the number of bits necessary to encode the source toward a theoretical minimum. MPEG 2, shown in the lower portion of Fig. 3, provides a practical realization of the information theory by a complex set of transform, run-length, and other source codes. The MPEG algorithm further reduces the information content by selective removal of detail not subjectively important. Channel-coding theory indicates that channel codes exist that can drive the error rate toward zero while not driving the useful throughput toward zero. In 1966 Forney (7) demonstrated a path to realization of this theory by showing that concatenating multiple, simpler channel codes can create a powerful channel code. Figure 3 illustrates a DTH implementation using concatenated convolutional and Reed-Solomon (RS) codes. A bit interleaver is also used to

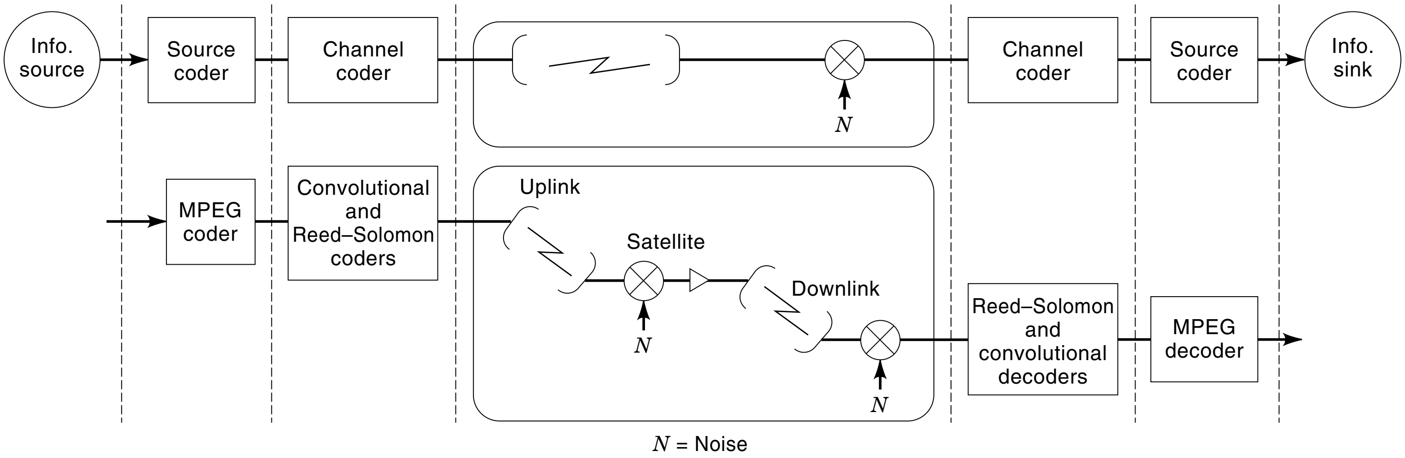

Figure 3. Theoretical source and channel coding are currently implemented by distinct source and channel coding processing.

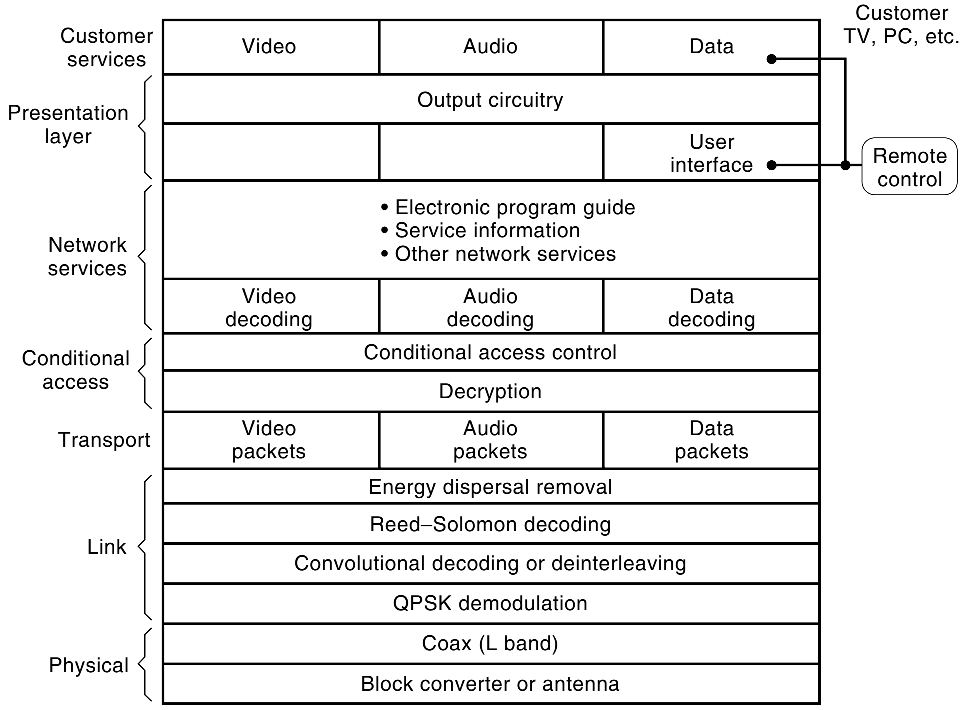

Figure 4. Layered or protocol model provides a practical decomposition of functions in a generic DTH integrated receiver decoder. Source: International Telecommunication Union, Document 10-11S/TEMP/18, Fig. 1.

"smooth" burst error sequences entering the RS decoder. (See also the articles Channel capacity, Channel coding, and Digital radio.)

Layered Model

Figure 4 provides a "layered" or "protocol" model for DTH systems (8). The layers shown are for the consumer electronics part of the system, but of course the same layers are necessary within the broadcasting facility equipment. As in layered, communications protocols, it is intended that the design tradeoffs of one layer do not interact with the design tradeoffs of the adjoining layers. For example, the design of MPEG decoder chips is largely independent of the design of the video output circuitry, which may be targeted for either NTSC, phase alternation line (PAL), or sequential couleur avec memoire (SECAM) television receivers. As another example, the MPEG coder to decoder syntax was largely designed without great concern about the specific error characteristics of the channel. However, to improve recovery in the event of channel errors, the MPEG standard does include a Macro Block Slice structure that generally limits error propagation to a portion of a frame.

Each layer is discussed in the following and in the subsequent sections entitled "Transmission" and "Compression." The realization of these protocol layers is discussed in the section entitled "Consumer Electronics."

Physical Layer. The physical layer at the bottom of Fig. 4 presents the RF to intermediate frequency (IF) LNB converter and the resulting IF interface to the digital receiver itself. An IF frequency starting at 950 MHz is typical but not required (8).

Link Layer. This layer is discussed in detail later in the section entitled "Transmission."

Transport Layer. The transport layer is a multiplexing layer or, for example, the systems layer of the MPEG 2 standard. In each format given in Ref. 8, this layer provides common, fixed-length packets for all service types including video, audio, data, or overhead data such as electronic program guide information. Fixed-length packets ease high-speed processing and use of direct memory access.

Conditional Access Layer. This layer provides decoding of specialized conditional access (CA) packets, sometimes called entitlement management messages (EMMs) and entitlement control messages (ECMs) (9). The EMMs give instructions to the subscriber electronics regarding the authorized *entitlements,* for example, current subscriptions or pay per view status. The ECMs indirectly provide cryptographic keys for decryption of the individual services. In several systems these packets are passed from the receiver to a smart card with an embedded secure microprocessor. The microprocessor decodes ECMs and returns the corresponding keys. A decryption circuit within the receiver uses the keys and provides decrypted packets for each service to the network services layer. The receiver to microprocessor interface is often similar to the ISO standard (10). (See also the article Cryptography.)

Network Services Layer. This layer delivers the underlying DTH technical services. These services include video plus audio or "television," stand-alone audio services, and data delivery services. Separate processes handle the decompression of each service type. For example, video-decompression algorithms are quite distinct from those used for audio decompression. Video compression is discussed in greater detail later in the section entitled "Compression." Other network services include decoding of the electronic program guide and service information syntax.

Presentation Layer. This layer puts the network services in final form for the end user. The layer includes the NTSC or PAL encoders and output circuitry and the on-screen user interface. Although the electronic program guide information delivered by the network is common to all receiver types, each receiver designer may choose a unique user interface concept. For example, for a typical television program schedule grid, the grid extent (that is, numbers of view channels and time extent) and the color scheme are entirely up to the designer. The presentation layer also receives inputs from the user remote control, which is typically linked to the receiver using infrared or RF.

Customer Services Layer. In most DTH systems the customer provides the final display device such as the television or personal computer. This key assumption bounds the complexity of the satellite receiver and defines the characteristics of its output circuitry. For example, although a typical all-digital DTH system can deliver a three-component television signal, most existing televisions in the United States accept only a composite NTSC input. Since many new sets in the United States also accept a "separate chroma/luma" S-video signal, many satellite receivers in the American marketplace have supplied an S-video output in addition to the composite output. Figure 4 shows the remote control interfacing with both the presentation layer (user interface) and the customer services layer. The latter interface permits control of the display device by the same remote control device—for example, the remote may control the television volume level.

COMPRESSION

Fundamentals

Source coding may be lossless and permit a complete reconstruction by the source decoder, or source coding may be lossy and trade the quality of the reconstructed signal against the bits needed to transmit or store the signal. The nature of the compression algorithms vary with the signal type, its intended audience, and the cost relationship between the value of "saving bits" versus the value of the codec development and production. Reference 11 provides an excellent overview of the television compression state of the art through 1994. (See also the article IMAGE PROCESSING.)

The MPEG 1 (4) and MPEG 2 standards (5) have been broadly deployed in consumer products. The MPEG 1 standard is intended for noninterlace video and data rates up to about 1.5 Mbit/s. The MPEG 2 standard accommodates both noninterlace and interlace video, standard definition applications up to about 10 Mbit/s, and high-definition formats at bit rates up to about 15 Mbit/s to 50 Mbit/s. Note that while these standards provide details on the syntax and semantics between the encoder and decoder and are specific to a standard decoder, they say very little about the encoder. They are very abstract and do not dictate the technology of implementation. Both standards utilize two distinct processes in tandem to achieve high compression levels: discrete cosine transform (DCT) coding and motion-compensated interframe prediction. The MPEG 2 standard makes more complex algorithms available for motion compensation with interlace video. The discussion that follows provides a very simplified description of MPEG processing.

Discrete Cosine Transform Coder

Figure 5 illustrates the first major MPEG process, a DCT of pixel element values, the *lossy* quantization of these values, and then the *lossless* encoding of the result. Consumer television signals are acquired and displayed as line-scan images, but since substantial spatial redundancy exists, the line-scan images are first converted to 8 × 8 pixel blocks for MPEG processing. The DCT represents the horizontal and vertical information in the block using cosine functions as the basis vectors. The quantization step ignores the near-zero coefficients and tends to concentrate the energy in the transform domain into the low-frequency components. The "zigzag" read-out of the coefficients starts with the dc coefficient and proceeds in zigzag fashion toward the highest frequency vertical and horizontal component. If insufficient bits are available, the higher-frequency coefficients may not be encoded. The next processing steps use tables of run-length and variable length codes, which, based on experiment, will require the lowest average number of bits to represent the coefficients. The run-length codes use short codes for very likely bit sequences and long codes for less likely sequences. The variable length codes are created such that no codeword is the prefix of another codeword. The buffer feedback path recognizes that image redundancy varies substantially across the blocks of a given image, but that for most applications the required output bit rate must be constant. As buffer fullness approaches, quantization can be increased, the bit rate reduced and, unfortunately, the quality will be reduced as well. Note that in multichannel systems, the output of a single encoder need not be at a fixed bit rate. In a DTH system, when a buffer strategy is used across all the video channels carried in a single stream, the technique is called statistical multiplexing.

In MPEG the spatial DCT coder described above is supplemented with an interframe predictor to also exploit the temporal redundancy of a given pixel block. Since motion within the image will cause the pixel values to "move" across the frame, the MPEG algorithms also include the technique discussed in the following.

Motion-Compensated Interframe Prediction

In MPEG, *motion compensation* determines the translation vector of 16 × 16 pixel blocks of luminance (called macroblocks) across multiple frames. Redundancy reduction is

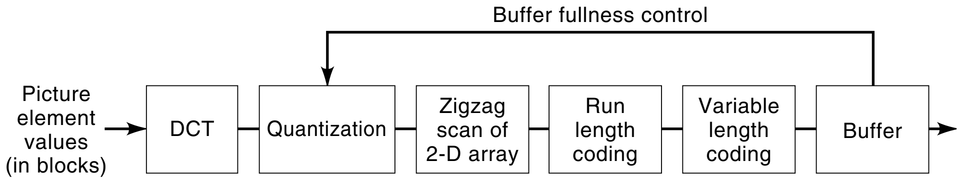

Figure 5. The discrete cosine transform (DCT) encoder path with its buffer control feedback loop is one of two major elements of the MPEG encoding process.

achieved by transmitting the vectors and quantized prediction errors, rather than the blocks, and further efficiencies are achieved by differentially encoding the vectors and also using variable length codes. The vectors are determined by finding the best macroblock match in the previous (and possibly also the future) reference frame. These searches generally are restricted in horizontal and vertical extent and can be very computationally intensive.

The MPEG 2 algorithm is more sophisticated than MPEG 1 in several areas, particularly motion-compensation modes. Both compression schemes permit forward prediction, backward prediction, and interpolated prediction between images. The images may be either video frames or fields. MPEG 1 can use only frame-based prediction; however, MPEG 2 optionally can use field-based prediction, which allows increased coding efficiency for interlaced video. From video material in which the motion is slow, frame prediction is more efficient and MPEG 2 performs similarly to MPEG 1. As motion increases, field-prediction coding becomes more efficient.

The MPEG 2 tool kit is very complex. It is impractical to recreate the entire tool kit in every application. The MPEG 2 group has therefore defined a handful of subsets or profiles of the full syntax. Also, within a profile, sets of parameter constraints have been identified as levels, with each higher level including all constraints from the lower levels.

TRANSMISSION (OR LINK LAYER)

Link Equation, Antenna Size, and Coverage

The most fundamental design equation in a DTH satellite system is the communications link equation. Ignoring uplink noise and interference contributions, the downlink carrier power (C) to noise power density (N_0) ratio is, in decibels, as follows (12):

$$\frac{C}{N_0} = \mathrm{EIRP}\Big|_{\mathrm{s}} - \mathrm{BO}_0 - L_{\mathrm{d}} + \frac{G}{T}\Big|_{\mathrm{e}} - k - L_{\mathrm{r}}\ \mathrm{dB}\cdot\mathrm{Hz} \qquad (1)$$

where the $\mathrm{EIRP}|_{\mathrm{s}}$ is the effective power of the satellite with respect to an isotropic radiator, BO_0 is the backoff of the satellite transmitter with respect to saturation, L_{d} is the free space loss at the carrier frequency, $G/T|_{\mathrm{e}}$ is a receive figure of merit for the DTH subscriber terminal, k is Boltzmann's constant (-228.6 dB · W/K · Hz), and L_{r} is the link loss due to rain. Figure 6 illustrates the definition of these link parameters. For a typical DTH design, each satellite transmitter handles a single carrier, so carrier intermodulation is not a concern and the transmitter output backoff is nominally zero. As a reference case, assume a downlink frequency of 12 GHz, a path loss of -205.8 dB, and a clear weather situation with $L_{\mathrm{r}} = 0.0$ dB. Equation (1) then becomes simplified to

$$\frac{C}{N_0} = \mathrm{EIRP}\Big|_{\mathrm{s}} + \frac{G}{T}\Big|_{\mathrm{e}} + 22.8\ \mathrm{dB}\cdot\mathrm{Hz} \qquad (2)$$

Using the parameters of Ref. 13 as an example, the typical edge of coverage EIRP is 52.0 dB · W and the subscriber terminal G/T is 11.3 dB/K for a 45 cm dish. The clear-weather, edge-of-coverage performance is then

$$\frac{C}{N_0} = 86.1\ \mathrm{dB}\cdot\mathrm{Hz} \qquad (3)$$

The required C/N_0 is determined by the information bit rate and the required E_{b}/N_0, energy per information bit over the noise density, for the system's modulation and coding with an implementation margin. The equation relating the two ratios is

$$\frac{C}{N_0}\Big|_{\mathrm{req}} = \frac{E_{\mathrm{b}}}{N_0}\Big|_{\mathrm{req}} + r + R\ \mathrm{dB}\cdot\mathrm{Hz} \qquad (4)$$

where r is the coding rate and R is the transmission rate in dB · Hz. The information bit rate is the product of the code rate and transmission rate, which is expressed as a sum in decibels.

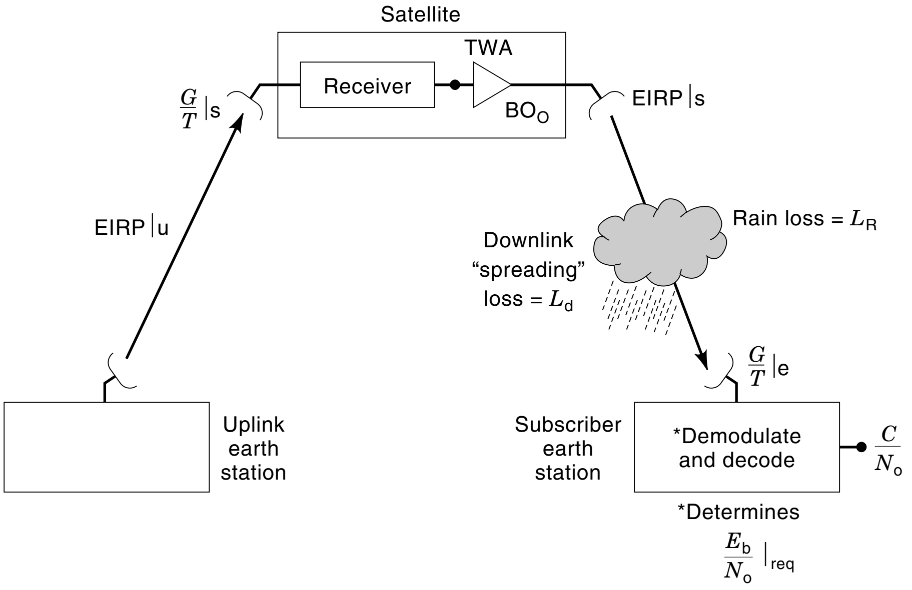

Figure 6. For design analysis purposes, the end-to-end DTH link is often split into "uplink" and "downlink" models. The downlink model assumes a noiseless uplink with the desired signal injected at the satellite TWTA input.

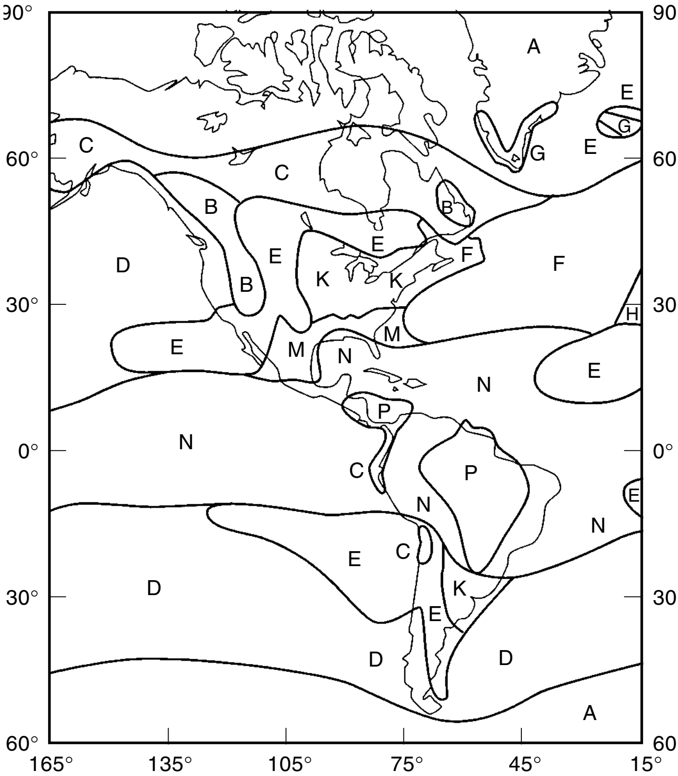

Figure 7. The ITU rain attenuation model for the Broadcasting Satellite Service (12.2 GHz to 12.7 GHz) has divided the Americas into a number of zones. The model assumes the same rain rate statistics across all areas of a given zone. Source: International Telecommunication Union, Radio Regulations, Vol. 2, Appendix 30, Fig. 3 (see Ref. 16).

Using $r = \frac{49}{64}$ and $R = 40$ Mbit/s (for an information rate of 30.6 Mbit/s or 74.9 dB · Hz), and a threshold E_b/N_0 value of 7.8 dB · Hz, then

$$\left.\frac{C}{N_0}\right|_{\text{req}} = 82.7\ \text{dB}\cdot\text{Hz} \qquad (5)$$

The clear-weather, edge-of-coverage performance is then the difference of Eqs. (3) and (5), or 3.4 dB. This is the clear-weather margin for a 45 cm dish for the parameters of Ref. 13. Below a 30 cm diameter (for BSS systems in the Americas), intersystem interference sources due to adjacent satellites cause the simplified analysis used above to become quite inappropriate. Above about 90 cm, the narrow beam of the subscriber antenna may actually be detrimental to satisfactory performance. For narrow-beam subscriber antennas, small satellite stationkeeping errors may cause the line of sight to move outside the subscriber antenna's main beam.

Propagation Effects at 12 GHz

In the preceding link example, the value L_r is a link margin against rain and other propagation phenomena. In fact, a system design is typically based on statistical and geometric models to predict the rain degradation along the line of sight. Although a variety of propagation-related impairments can occur, the dominant effects are due to rain and wet snow and result in signal attenuation and attendant increases in the received "sky" noise. Experimentation work, as described in Ref. 14, has compared the rain attenuation along a given path with the rain rate measured on the path and found that the specific attenuation (dB/km) can be approximated by the expression

$$\text{Specific attenuation} = a\mathbb{R}^b \qquad (6)$$

where $\mathbb{R}$ is the rain rate in the millimeters per hour and a and b are frequency- and temperature-dependent constants.

With this fundamental model, worldwide environmental information and a geometric model of the "rain cylinder" along the line of sight, comprehensive models have been developed for DTH system design. Figure 7 shows the rain regions assumed by the International Telecommunication Union (ITU) for BSS planning for the Americas. Figure 8 illustrates the attenuation predicted by the ITU model for Region K of the Americas. The outage value assumed in Fig. 8 (1% of the worst-case month) is a requirement that should be reevaluated by the designer in each new application.

Interference

In addition to rain degradations, DTH designs must consider intrasystem and intersystem interference. Interference into the subscriber dish is a primary concern. Received interference includes cross-polarized, co-frequency, intrasystem interference, interference from other satellites operating at adjacent orbit locations, and emissions from terrestrial users of the same frequency band. The Broadcasting Satellite Service was carefully planned to separate orbital "slot" assignments

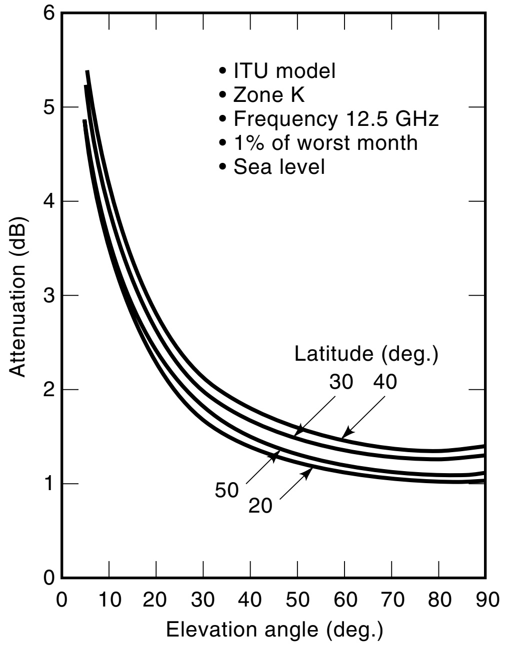

Figure 8. Rain-related downlink attenuation decreases as the elevation angle above the horizon increases but the attenuation does not increase monotonically with latitude. These curves are based on the ITU propagation model and apply to rain zone K. Source: International Telecommunication Union, Radio Regulations, Vol. 2, Appendix 30, Fig. 4h (see Ref. 16).

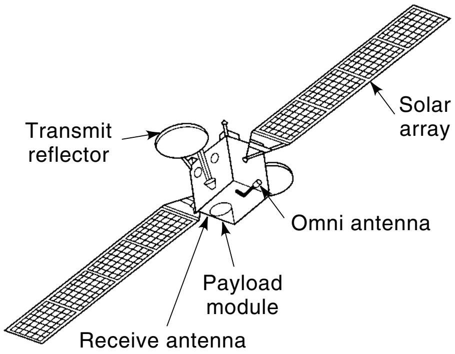

Figure 9. The deployed configuration of DTH satellites is dominated by the solar panels used for power generation. Courtesy of DIRECTV, Inc.

for satellites with beams with common coverage (15–17), for example, for the United States the primary orbital assignments have 9° of longitude separation. In the Federal Communications Commission's (FCC's) Fixed Satellite Service assignments at 11.7 GHz to 12.2 GHz, the satellites are separated by as little as 2° of longitude; the 2° separation causes dishes of less than 60 cm in diameter, with relatively little spatial isolation, to have generally unacceptable adjacent satellite interference. In the BSS in the United States, the use of 45 cm dishes is a common practice and one service provider has announced plans to use 30 cm dishes.

Satellite Design

Figure 9 illustrates a typical DTH satellite platform. All operational DTH systems have used satellites in geosynchronous orbit (GSO) with microwave frequency-translation repeaters. After placement in a GSO, the satellite orbital period is equal (synchronous) with the rotational period of the earth, and the satellite appears to be stationary over a given longitude at the equator. This greatly simplifies the design of the millions of receive terminals that point toward the satellite.

A frequency-translating repeater typically receives an uplink carrier via the receive coverage antenna beam, mixes the signal to the downlink frequency, and then amplifies it for transmission to the transmit coverage beam. This type of translating design is highly reliable and flexible. The receive and transmit coverages need not be identical—for example, for a typical national system the receive beam coverage may be the 48 contiguous states while the transmit beam coverage may consist of all 50 states. (See SATELLITE ANTENNAS.) The DTH satellite's total dc and total RF power levels are key attributes since most of the satellite weight and hence cost are involved in generating high power levels. This relationship between weight and cost is largely due to the high cost and relative unreliability of launch vehicles. As one example, the Galaxy Latin America satellite launched at the end of 1997 had an end-of-life solar array power capability of about 8.0 kW. (See Ref. 18 and SOLAR CELLS.)

The satellite electronics associated with processing and amplifying a single carrier, such as a multiplexed digital television carrier, is called a satellite *transponder*. The final output stage or transmitter is normally a traveling wave tube amplifier (TWTA), a device with very high gain, high efficiency, perhaps in excess of 50%, and wide bandwidth. Although high-power TWTA reliability was a DTH design issue through 1990, dozens of transmitters with power levels above 100 W have operated without apparent incident for more than three years during the 1990s. (See TRAVELING WAVE TUBES.)

Regulatory Considerations

Direct-to-home systems are typically regulated at the national level. Until recently virtually all nations had a government-owned Post, Telephone, and Telegraph (PTT) or quasi-government agency that owned and operated all national telecommunications facilities. With the worldwide trend toward commercialization and competition, the government role is tending toward regulation of DTH businesses via RF and business licensing. For example, in Japan, the Ministry of Post and Telecommunications (MPT) has allowed three new commercial DTH businesses to compete with the traditional quasigovernment broadcaster NHK. Each of these businesses has required MPT approval over multiple aspects including the provider (consignor) of each programming channel, the content of the channel, the business viability of each channel, the RF licensing of the uplink site, and the RF licensing of the satellite.

The situation in the United States is somewhat unique in that competing private telecommunications businesses have existed since the 1970s. The FCC licenses and regulates satellite systems primarily via licensing of the satellites themselves. Small receive-only antennas do not require licensing, and the FCC has ordered that, in general, dishes smaller than 1 m cannot be regulated by state or local authorities (19).

Broadcasting from one nation into another commonly requires official *landing rights* in the distant nation, particularly if the broadcaster intends to collect subscriber fees. Issues of frequency use and coordination between nations are handled by an agency of the United Nations, the International Telecommunication Union (20). The regulatory agency, that is, the PTT, MPT, or FCC, of each UN nation sends representatives to various ITU working groups to establish mutually agreed international regulations. In general, each agency makes the international regulations a part of their national regulations; the ITU itself has no powers of enforcement. The ITU has established a number of frequency bands for satellite communications; for DTH applications the bands utilized have been both in the FSS and BSS. The FSS name comes from the fact that, for frequency coordination purposes, the transmitters and receivers are assumed to be at fixed locations, that is, not mobile. The BSS bands also assume "fixed" RF sources but with the added assumption that the primary usage is direct broadcast. In the early 1980s when the international BSS arrangements were competed, this distinction was quite important since the representatives to the ITU sessions wished to be sure that their nations would someday have the benefit of DTH service. Thus the use of the BSS band (around 12 GHz) has been strictly planned such that every nation existing at the time of the agreement has a specific set of assigned frequencies, polarizations, and satellite antenna coverage. Note that the difference between the FSS and BSS bands is entirely regulatory, not technical—in fact, the BSS band in the United States is the same frequency as the FSS band in Japan and vice versa.

The ITU regulations are based on dividing the world into three regions with specific geographic boundaries. These regions are roughly defined as follows: Region 1 consists of Europe, Africa, and the former Soviet Union; Region 2 consists of the Americas; and Region 3 consists of Asia, excluding the former Soviet Union. Among these different regions the specific regulations can vary substantially, and within a given country the national administration may impose additional regulations. For example, under ITU auspices the BSS frequency bands vary by region, the frequency assignments vary by country, and each country assigns frequencies to a system or company. The downlink plan for all regions is contained in Appendix 30 of the ITU Radio Regulations (16). The uplink or "feeder" link plan is contained in Appendix 30A of the ITU Regulations (17). The 1997 World Radio Conference made changes to certain parameters for Regions 1 and 3 only.

Traditionally, telecommunications standardization has been performed by international groups such as the ITU, International Organization for Standardization (ISO), International Electrotechnical Committee (IEC), and the Joint Technical Committee (JTC1) of the ISO and IEC (21). As a growing trend, standards are being addressed by regional groups such as the European Telecommunications Institute (ETSI) or the T1 committee in the United States, an organization accredited by the American National Standards Institute. Additionally, specialized, ad hoc groups have been formed to address certain areas of technology, for example, the Asynchronous Transfer Mode (ATM) Forum, the Internet Engineering Task Force (IETF), and the Digital Audio Visual Council (DAVIC).

The ITU has developed a standard for "Digital Multiprogramme Television Emissions by Satellite," (8) but this is an international recommendation, not a requirement, unless implemented by a national agency as a national standard. This ITU recommendation includes three closely related broadcast formats that can be decoded by the same or similar receiver circuitry. Table 1 compares the characteristics of the three formats. All three utilize QPSK modulation, concatenated convolutional and Reed-Solomon coding, MPEG compression, and fixed-length transport packets.

Table 1. Summary of ITU Direct-to-Home Formats

Function	System A	System B	System C
Randomization for energy dispersal	Yes	Explicit	Yes
Reed–Solomon outer code	(204, 188, $T = 8$)	(146, 130, $T = 8$)	(204, 188, $T = 8$)
RS field generator polynomial	$X^8 + X^4 + X^3 + X^2 + 1$		
Interleaving	Forney	Ramsey II	Forney
Inner coding	Convolutional, $K = 7$		
Basic code	$\frac{1}{2}$		$\frac{1}{3}$
Generator polynomial	171, 133 (octal)		117, 135, 161 (octal)
Forward error correction (FEC)	$\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{5}{6}$, and $\frac{7}{8}$	$\frac{1}{2}$, $\frac{2}{3}$, and $\frac{6}{7}$	$\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{3}{5}$, $\frac{4}{5}$, $\frac{5}{6}$, $\frac{5}{11}$, and $\frac{7}{8}$
Signal modulation	QPSK		
Symbol rate	Variable	20 Mbaud	19.5 and 29.3 Mbaud
Transport layer	MPEG 2	System B	MPEG 2
Packet size (bytes) [payload]	188 [184]	130 [127]	188 [184]
Identification ID (bit)	13	12	13
Statistical multiplexing	Not restricted	Capable	Capable
Method of synchronization for video and audio	Time stamping (27 MHz reference)		
Video source decoding			
Syntax	MPEG 2		
Levels	At least main level		
Profiles	At least main profile		
Audio source decoding	MPEG 2 layers I and II	MPEG 1 layer II (included in MPEG 2)	**ATSC A/53 or MPEG 2 layers I and II
Typical transponder bandwidth (MHz)	Not specified	24 or 27 MHz	24, 27, or 36 MHz
Selectable conditional access	Yes		
Service information	*ETS 300 468	System B	**ATSC A/56+†SCTE DVS/011
Electronic program guide	*ETS 300 707	System B	User selectable
Teletext	Supported	Not specified	
Subtitling	Supported		
Closed caption	Not specified	Yes	
Delivered TV standards	Not specified	NTSC and PAL M	NTSC and PAL
Aspect ratios	4 : 3 and 16 : 9 (2.21 : 1 Optionally)	4 : 3 and 16 : 9	4 : 3 and 16 : 9
Video resolution formats	Not restricted	MPEG subset	MPEG subset
Frame rates (frames/s)	Not specified	29.97	25 (PAL) 29.97 (NTSC)
Compatibility with other MPEG 2 delivery systems	††ISO/IEC 13818	Some processing required	††ISO/IEC 13818

* European Telecommunications Standards

** Advanced Television Systems Committee (standards)

† Society of Cable Television Engineers

†† See Ref. 5.

In Europe the Digital Video Broadcasting (DVB) Project to develop specifications for all aspects of digital television broadcasting was launched in 1993, following a two-year effort. Since producing its first digital satellite standard, the DVB Project has developed specifications, guidelines, and recommendations for the many ancillary parts of digital broadcasting. These have been accepted as standards for DTH systems by more than 200 broadcasters, manufacturers, network operators, and by regulatory bodies in over 30 countries (9).

In Japan, the Association of Radio Industries and Businesses (ARIB) has selected a DVB variant as the standard for digital CS systems (22). In the United States, the FCC has not required specific requirements for DTH services.

In general, these various standards have dealt with the link, transport, and network services layers, but not the conditional access layer. Certain governments have standards to restrict or specify the encryption method controlled by the conditional access system. For example, Japan's MPT has specified the encryption algorithm for the new digital CS systems. Recently, DVB, DAVIC, and the Advanced Television Systems Committee (ATSC) in the United States have begun work on conditional access standardization. (See also TELEVISION BROADCAST TRANSMISSION STANDARDS.)

CONSUMER ELECTRONICS

Consumer electronics equipment for DTH applications has achieved very low cost, high performance, and excellent perceived value by carefully designed very-large-scale integration (VLSI) and mass production. By use of standards, for example, MPEG 2, and standard techniques, many VLSI have been used in more than one platform and thus achieved greater economies of scale.

Outdoor Electronics

The offset fed parabolic reflector continues to be the dominant antenna type due to its simplicity and high gain for a given aperture size. The offset geometry achieves an aperture efficiency greater than 60% by eliminating the "feed blockage" present in a focus fed geometry. Figure 10 shows a 45 cm parabolic dish, digital receiver, and remote control produced by Panasonic in 1997 for the CS market in Japan. Single-polarization, fixed-scan, phased array antennas are also used, but generally not where their size would be greater than 60 cm × 60 cm, when distribution losses become significant.

Receivers

In the design shown in Fig. 10, the receiver supplies dc power to the outdoor electronics via the coaxial cable delivering the digital signals to the receiver. Additionally, biasing this supply voltage above or below the nominal value implements polarization selection at the feed. Figure 11 gives a reference architecture for a digital DTH receiver (8). This common architecture can be applied to any of the three digital formats contained within the reference.

Hardware. In implementing the reference hardware architecture of Fig. 11, the underlying large-scale integrated circuits (LSI) have since 1994 undergone multiple stages of evolutionary development. As an example, Table 2 summarizes the LSI evolution of the RCA-brand receivers produced for the United States marketplace. Each generation has seen greater levels of integration (23) with the fourth generation being a "two-chip" receiver.

Figure 10. Direct-to-home consumer electronics includes a *mini-dish,* a receiver, and remote control. This Panasonic equipment for the DIRECTV JAPAN system went on sale in December 1997. Courtesy of Matsushita Electric Industrial Co., Ltd.

Similar levels of LSI integration are also expected with the availability of such chips as the Texas Instruments Series AV 7000 shown in Fig. 12. This chip provides the equivalent of 2.5×10^6 transistors using 0.35 μm complementary metal oxide semiconductor (CMOS) technology. Advance information (24) indicates that this circuit will incorporate the following:

32-bit reduced instruction set computer (RISC) central processing unit (CPU) [40 million instructions per second (MIPS)]
Advanced graphics accelerator
Memory manager
Transport/decryption (DES)
MPEG 2 video decoder (MPEG 1 and MPEG 2)
Audio decoder (MPEG 1)
NTSC/PAL encoder

To complete a typical receiver, the designer will add the following:

Tuner
Link integrated chip
Memory [read-only memory (ROM), random-access memory (RAM), dynamic RAM (SDRAM)]

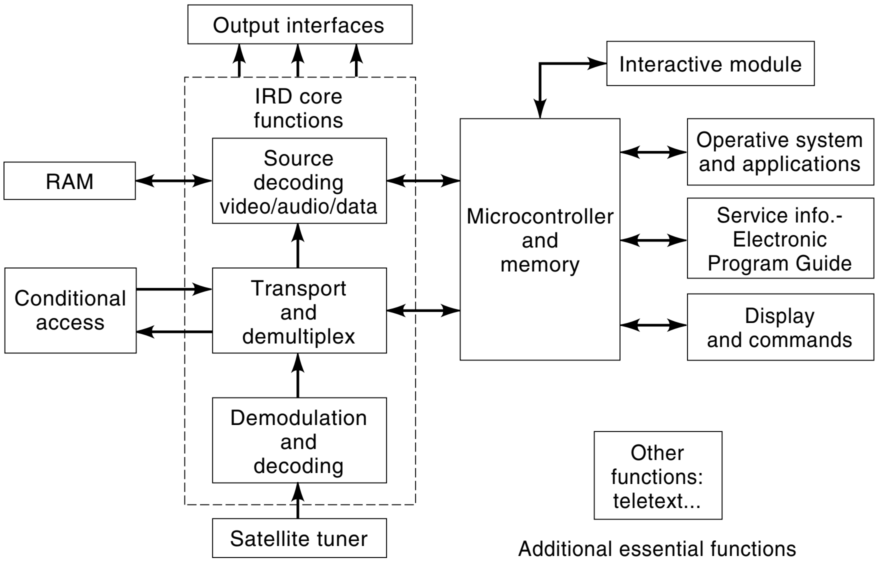

Figure 11. The ITU generic reference model for a satellite integrated receiver decoder. Source: International Telecommunication Union, Document 10-11S/TEMP/18, Fig. 2.

Smart card
Telephone modem
Other peripherals

The AV 7000 chip also provides an interface to external consumer electronics or computer devices using the IEEE 1394 serial digital protocol.

Software. Software architectures have been driven by the functionality of the major VLSI. The "transport" chips have provided some degree of logical filtering of the high-speed data streams—and hence not required filtering by the primary processor. The MPEG chips have, in general, relied on the processor to perform group of pictures (GOP) and picture sequence level processing. The primary processor also typically handles program guide and user interface tasks.

From a subscriber standpoint new product generations have exhibited faster response times and improved graphical interfaces. As a point of reference for 1998 technology, the Texas Instruments AV 7000 chip (24) will provide graphics support for up to eight windows, 8 bit color depth, 16 levels of blending and transparency, overlapping windows, and other features.

Recent products have also included *interactive* or *multimedia* software layers, which include, for example, Panasonic's DVX™ for DIRECTV JAPAN and Thomson Sun Interactive LLC's OpenTV™. The latter, a forerunner of an emerging interactive services industry, began in 1994 as an alliance of Thomson Multimedia and Sun Microsystems. OpenTV supplies interactive operating systems and services for digital receivers used by pay-television services, among other activities (25).

RECENT DEVELOPMENTS

Technology

Technological progress continues in most disciplines important to DTH digital systems. Satellite manufacturers have announced platforms with total dc power levels of at least 15 kW (26). With a power-generation capability four times that of DTH satellites launched as recently as 1995, these new

Table 2. Evolution of LSI in RCA-Brand DSS™

	First Generation	Second Generation	Third Generation	Fourth Generation
Initial Retail Availability	June '94	Jan. '96	Jan. '97	'98–'99
Major large scale integrated circuits (LSI)	Microprocessor	Microprocessor	ARM IC	DXX[a]
	Transport/Decrypt	Transport/decrypt		
	QPSK demod.	Link IC	Link IC	Link IC
	Convol. decoder			
	RS decoder			
	Video decompression	MPEG A/V	MPEG A/V	DXX[a]
	Audio decompression			
	NTSC encoder	NTSC encoder	NTSC encoder	
	Telephone modem	Telephone modem	Telephone modem	Telephone modem
	Video DRAM	Video DRAM	Video DRAM	Video DRAM

Information courtesy of Thomson Consumer Electronics, Inc.

[a] Single chip.

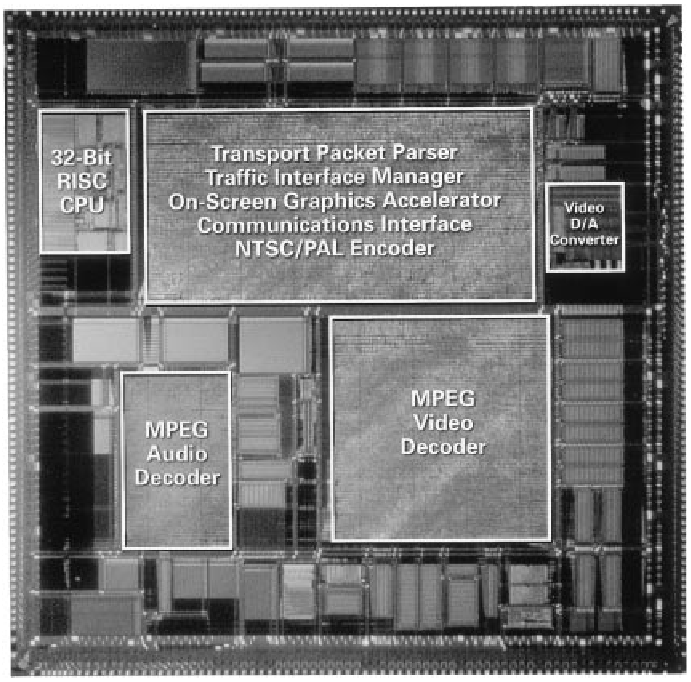

Figure 12. Rapid VLSI progress now permits a single chip to provide all DTH receiver core functions and many secondary functions, such as a microprocessor. Copyright © 1998, Texas Instruments Incorporated.

platforms may be in orbit before the year 2001. Modulation and coding show continuing improvements, particularly in turbo coding (27), and advanced modulation formats with higher information content per unit bandwidth (bits per sec/Hz) (28) are under consideration in new system designs. Compression standards development continues with the MPEG 4 standard (29), planned for final approval in late 1998 for version 1 and late 1999 for version 2. The MPEG 4 architecture permits different compression algorithms to be applied to different source material. The proposed inventory of algorithms includes image decomposition into multiple objects and the existing transform-based algorithms such as MPEG 2.

Proposed Systems and Services

New system filings in 1997 at the FCC included a DTH system (30) operating at a downlink frequency of 17.3 GHz to 17.8 GHz, a band commonly referred to as the *Ka band*. This system filing proposed to accelerate initial use of this frequency band as a new *BSS expansion band*, planned by the ITU to first come into operation in 2007. Also in 1997 a group proposed a system called Skybridge (31), which would reuse the existing BSS band but with nongeosynchronous satellites. The system design uses 64 satellites in 1457 km altitude orbits for a variety of telecommunications services. The plan suggests that frequency reuse can be achieved by not broadcasting from a particular Skybridge satellite to a particular region unless, as seen from the user location, the separation angle is sufficiently large between the line of sight to Skybridge and to the geosynchronous satellite arc. According to the Skybridge plan, if the separation angle is large, and certain other conditions are met, the discrimination of the user antenna will lower the Skybridge interference to an acceptable level.

In the area of new service offerings, the Hughes DirecPC™ service is one example of DTH satellite broadcasting to a personal computer platform. This service, available in the United States, Japan, and Europe, utilizes a small, outdoor dish and, installed in a conventional PC, a digital satellite receiver card. During 1998 in the United States, the DirecPC services includes both *pull* (two-way) and *push* (one way) Internet access. In early 1998, DIRECTV, Inc., demonstrated high-definition DTH broadcasting with delivery of 1280 × 1080 picture elements in interlaced signals to a television provided by Thomson Consumer Electronics. DIRECTV announced that it would initiate nationwide high-definition (HD) broadcasts before the end of 1998 and coincident with the first terrestrial digital broadcasts (32). (See also HIGH DEFINITION TELEVISION.)

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Reading List

For further reading and current information, please consult the World Wide Web sites listed below.

For general information about the major systems in the United States try the following:

DIRECTV	http://www.directv.com/
EchoStar	http://www.dishnetwork.com/
Primestar	http://www.primestar.com/
USSB	http://www.ussb.com/
SkyReport	http://www.skyreport.com/dthsubs.html//

Information about evolving standards can be found at the following:

ATSC	http://www.atsc.org/
DAVIC	http://www.davic.org/
DVB	http://www.dvb.org/
MPEG	http://drogo.cselt.it/mpeg

An “unofficial” but very useful MPEG site is as follows:

http://www.bok.net/~tristan/MPEG/MPEG-content.html

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DirecTV

DIRECT SEQUENCE MODULATION. See SPREAD SPECTRUM COMMUNICATION.

DISCHARGE, ELECTROSTATIC. See ELECTROSTATIC DISCHARGE.