CABLE HEADEND INTERFACES FOR DIGITAL TELEVISION

Mukta Kar, Ph.D., Majid Chelehmal, Ph.D., and Richard S. Prodan, Ph.D.
Cable Television Laboratories

Abstract

Advanced digital technology, combining compressed digital video with digital transmissions, can deliver multiple programs containing superior quality audio, video, and data, using the spectrum required for a single analog program. Broadcast affiliates will migrate to broadcasting digital signals starting in 1998, per FCC guidelines. By the year 2006, terrestrial broadcasting of analog TV should be retired and replaced by digital television (DTV).

Currently, most television viewers receive terrestrial broadcast signals over cable systems. An interface specification needs to be defined for receiving and processing the broadcasters' DTV signals compliant to the Advanced Television Systems Committee (ATSC) standard at the cable headend and through the subscriber receiver equipment. Such an interface specification must deal with some of the issues related to the integrated delivery of broadcast signals with other analog and digital signals originating from various sources.

This paper will explore the various types of signals, information, and associated interface mechanisms in the headend, and their relation to subscriber receiver equipment.

INTRODUCTION

Television has become the most popular medium for news, entertainment, education, and other information in the United States. Broadcast television signals are transmitted over media such as cable, air (terrestrial, MMDS, LMDS, etc.), or satellite. Broadcasters (cable, terrestrial, or satellite) represent independent enterprises free to make their own business decisions and to choose the broadcast contents desired by their subscribers. But in the national interest, broadcasters provide the general public with news, presidential addresses, and political debates of national importance. In the same light, local news and events must be delivered either by local cable or off-air broadcast services. More importantly, there must be a means to facilitate the pre-emption of regular programming with the Emergency Alert System (EAS) signal, from a central control facility, to all systems connected in a network.

Although there are various types of broadcasting entities in existence today, cable and terrestrial broadcasts reach the overwhelming viewer majority (satellites, and others, reach a small minority). In order to reach most of the U.S. viewers for emergencies, or for news of national and local interest, Congress instituted the "Must Carry" requirements that cable networks carry at least one local channel of each of the major terrestrial broadcast networks (ABC, NBC, CBS, PBS, etc.).

It has been proven in the laboratory, and in cable and satellite field testing, that compressed digital television technology is very spectrum-efficient. At the same time, it delivers superior quality video and audio compared to its analog counterpart. Another benefit of this digital technology is its flexibility. Enhanced television services provide internet access, home shopping, investing and banking from home, games, etc., in addition to passive entertainment. Technologists, businessmen, and policymakers agree that it is time to transition from analog to digital television. To facilitate the transition, the FCC has put forward guidelines requiring terrestrial broadcasters to switch from broadcasting analog television to broadcasting the new digital television standard, beginning in November 1998. Analog broadcasting will be retired completely, and the analog spectrum will be returned by the year 2006.

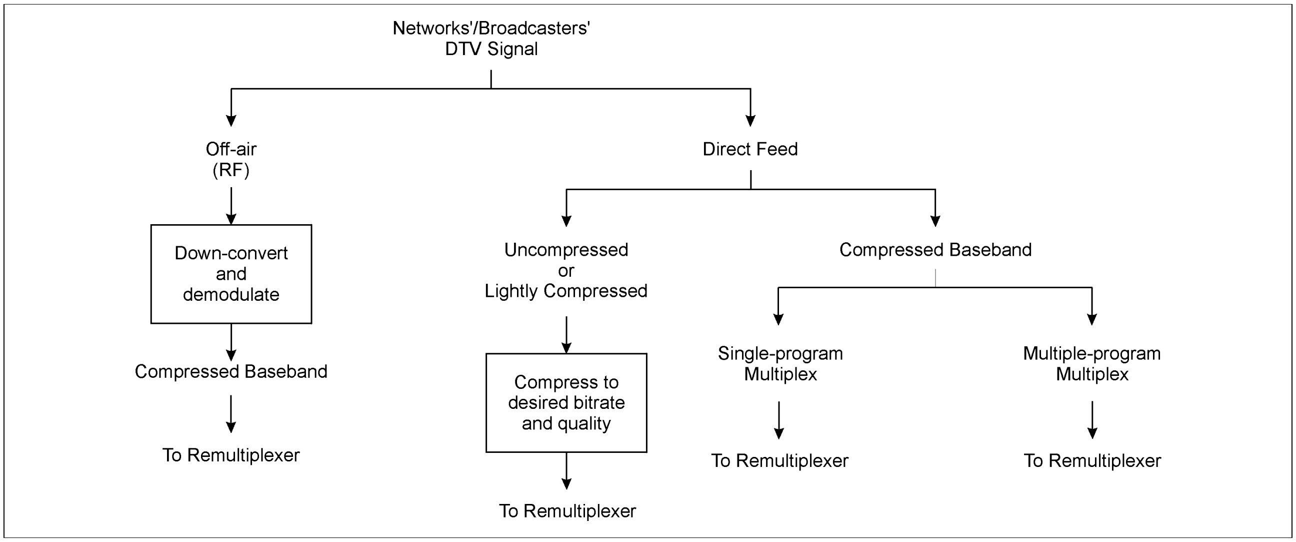

Figure 1. Various forms of digital television (DTV) signals

Terrestrial broadcasters will begin broadcasting a superior quality digital television (DTV) signal, in particular, high definition digital television (HDTV). Many viewers will be impressed with HDTV. Initially, some new HDTV receivers will be available when HDTV broadcasting begins. In addition to delivering superior picture quality, digital technology provides a higher efficiency in spectrum utilization and a higher level of security against theft of services. The gradual switch to digital technology will free up some physical channel capacity, which may be used to add new, or enhance existing, services.

Content providers will switch from distributing programming in analog to digital format. The cable industry needs to prepare to receive digital signals and to interface them seamlessly to headend equipment. Cable telecommunication engineers will have to deal with different signal types, which headends may transport, and which must interface with other headend equipment.

Figure 1 shows a typical combination of DTV/HDTV baseband signals. In the compressed domain, the combined signal is a single- or multiple-program MPRG-2 transport stream. The signals contained in the multiplexed transport stream originate in different formats and must be handled accordingly. Following are descriptions of some popular formats.

COMPRESSION FORMATS

Uncompressed Video Signals

The CCIR 601 digital format is usually the most popular. The luminance and chrominance (two color components) signals are sampled in a 4:2:2 structure with the resultant active picture size of 720 pixels by 486 lines (System M NTSC scanning). Each pixel is digitized with 8 bits (10 bits optionally). The bitrate required to transmit standard definition (SD) video is around 216 Mbits/sec (8-bit video) and greater than 1 Gbits/sec for high definition (HD) 8-bit video. The advantage of receiving uncompressed signals is that they can be compressed at the headend to the desired quality and bitrate. This provides flexibility, but requires an encoder for each uncompressed signal.

Compressed Video Signals

Any video signal, with bitrate reduced from its uncompressed rate by removing redundancy, can be categorized broadly as a compressed signal. Here it means specifically the main profile at main level (MP@ML) compressed signal for SDTV and main profile at high level (MP@HL) for HDTV defined in the MPEG-2 standard. The typical bitrate for a SDTV (720 x 480 pixels) signal is 2 to 6 Mbits/sec, and that of HDTV (1080 x 1920 interlaced) is 12 to 19 Mbits/sec. In either case, a compression ratio of 50 or better has been achieved. The sampling structure for the CCIR-601 standard is 4:2:2, but the MPEG-2 standard uses a 4:2:0 sampling structure. As a result, the MPEG-2 compression method sub-samples the chroma components of the video signal in both horizontal and vertical directions before compression. This is one of the main factors in achieving high compression with a minimal subjective loss in video quality. If this compressed signal has to be processed (decoded and re-encoded a few times), the picture quality of the compressed signal deteriorates significantly. Also, if video signals are compressed, the quality after the first compression cannot be improved by decoding and, subsequently, re-encoding at a higher rate. These shortcomings are mitigated by using lightly compressed signals.

Lightly Compressed Video Signals

A lightly compressed video signal is minimally compressed to around 45 Mbits/sec to reduce signal transmission bandwidth with nearly transparent picture quality. However, this type of signal needs to be decompressed and recompressed to a lower bitrate and quality for final distribution. The handling complexity of these signals is similar to that of uncompressed video signals. To preserve the loss in quality inherent in standard MPEG-2 compression, a profile known as 4:2:2 has been added to the MPEG-2 standard. In the 4:2:2 profile at main level (4:2:2P@ML), picture quality has been preserved in two primary ways. Unlike other profiles, chroma components have not been sub-sampled and the original CCIR 601 signal sampling structure remains. Greater quantizer precision may be used for encoding DC- and AC-coefficients of the 8 x 8 discrete cosine transform (DCT) block. This implies that the bitrate should be fairly high. For these reasons, the typical bitrate for the 4:2:2 profile is 20 to 50 Mbits/sec. It should be mentioned that at a higher bitrate, the 4:2:2 profile can provide a superior quality picture after several decoding and re-encoding iterations.

TRANSMISSION FORMATS

Off-air Signals

Off-air signals may be defined as modulated radio frequency (RF) signals which use free space as the medium of propagation and transmission. In this method, an RF-carrier is modulated by a digital baseband signal using a vestigial sideband (8-VSB) or a quadrature phase shift keying (QPSK) modulation method. Terrestrial broadcasters will use an 8-VSB DTV signal, and satellite networks will use QPSK-modulated carriers to distribute their content. Reception of these signals will be accomplished using an appropriate antenna and an integrated receiver decoder (IRD) to demodulate back to the baseband. The IRD provides the baseband multiplex signal. Some IRDs will have the capability of decrypting the compressed baseband signal. This signal may be used as input to a remultiplexer or as input for some other application. There is another option available for 8-VSB modulated signals—if the headend passes through them, then no demodulation is required. However, the signals need to be frequency-translated to a desired cable channel. This wastes channel capacity, since a quadrature amplitude modulation (QAM) cable signal carries 50 to 100 percent more payload.

Direct-feed Signals

Signals received through a guided medium, such as coaxial or fiber optic cable, to the headend may be considered direct-feed. Direct-feed provides a less noisy signal with a high signal-to-noise ratio (SNR), an advantage for analog signals. Analog signals may be received at the baseband or RF using direct-feed. For digital direct-feed, the RF-modulated signal provides little or no improvement over off-air RF signals above threshold, but can provide a consistent quality signal. Receiving a direct-feed baseband signal does not require an IRD for demodulation.

MULTIPLEXING FORMATS

Single-program and Multiple-program Multiplexes

A single-program transport stream multiplex, consisting of video, audio, data streams, and associated multiplexing information, is known as a single-program multiplex. A transport-stream multiplex consisting of two or more programs of video, audio, data streams, and associated multiplexing information, is known as a multiple-program multiplex. Content providers may distribute their programs to headends and affiliates as a single-program multiplex. Broadcasters may use either a single-program multiplex for HDTV, or a multiple-program multiplex for standard DTV, depending on the time of day. For example, broadcast MP@HL format (1920 x 1080 interlaced) for HDTV requires a bandwidth of 19 Mbits/sec and may be broadcast using a single-program transport stream multiplex. It is also possible to add one SDTV program to a lower bitrate HDTV program and broadcast as a multiple-program multiplex. For broadcasting SDTV programs, broadcasters may bundle several programs in a multiplex.

MULTIPLEXING OVERVIEW

Figure 2 shows a block diagram of an encoding system with an output multiplex bitstream consisting of one or more programs. The encoder compresses audio and video hierarchically into compressed data by removing spatial and temporal redundancies. It then encodes the compressed data using variable length code (VLC, a combination of run-length and Huffman codes). Encoded compressed streams of audio/video are known as elementary streams (ES). The compressed ES is broken into variable length packets containing one or more access units (frames). These variable length packets are known as packetized elementary streams (PES). The packetizer in the multiplexer combines PES packets into fixed-length units of 188 bytes—184 bytes used for payload of PES data and 4 bytes for headers. These fixed-length packets contain a packet identifier (PID) in one of the header fields, allowing easy separation and recombination of the component streams.

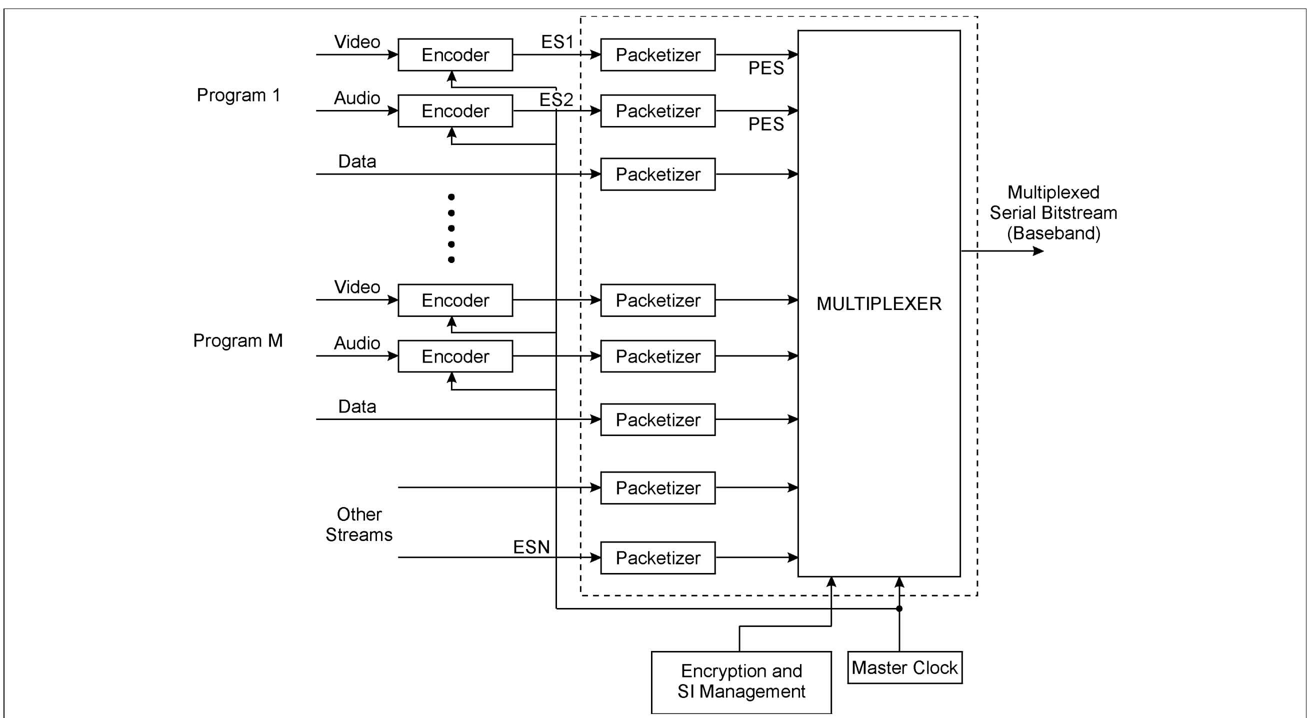

Figure 2. Block diagram of an encoding and multiplexing system

A multiplexer is a device in which various input and output streams may be programmed (*e.g.*, number of elementary streams and their bitrates, grouping elementary streams into programs, PID assignments to each ES, bitrate of the multiplexed output stream, etc.). Input packets (containing audio, video, and data streams) are multiplexed into a serial stream based on the input bitrates of the individual streams. A multiplexer also inserts packets containing system information describing the relationship of the various component streams into programs. This system information is essential at the receiving end for correctly demultiplexing the elementary streams. The multiplexer maintains a constant output bitrate. That is,

$$\sum_{k=1}^{N} bitrate(k) + bitrate(sys) \leq mux\ output\ rate$$

where: N = Number of ES inputs to the multiplexer;

bitrate(k) = bitrate of the individual ES;

bitrate(sys) = bitrate required by the multiplexer to insert system information such as PSI (program specific information), conditional access information (CAI), etc.;

Mux output rate = desired output bitrate of the multiplexer.

The multiplexer is also responsible for synchronizing all audio and video streams with a master clock. This is accomplished by inserting time stamps, such as a decode time stamp (DTS), a presentation time stamp (PTS) for audio/video frames, and a program clock reference (PCR) synchronized to a master clock, into the elementary streams. Another function of the multiplexer is to encrypt video and audio payload and other data (if necessary).

All multiplexed baseband signals are input to a remultiplexer in the headend, as shown in Figure 3. The functions of the remultiplexer are similar to those in the multiplexer, with some differences. A remultiplexer takes one or more transport stream multiplexes as input, and outputs a new multiplex using user-selected programs and data from input. To accomplish this, the remultiplexer has to decrypt and demultiplex the input streams, or simply unbundle the individual programs from the input multiplex. A new package of services is created from the operator-selected programs, with encryption as necessary. During demultiplexing, program specific information (PSI) is extracted from the input multiplexes and new PSI is inserted into the output multiplex in coordination with the headend management system.

Another important function of the remultiplexer is to remove timing jitter in the selected programs from the incoming multiplexes. During transmission due to nonuniform switching delay, jitter in PCR values is introduced. The PTS and DTS values of audio or video access units (AU) may not match with the PCR. For example, the DTS or PTS of the frame expired before the entire frame is available in the decoder buffer. To remove such transmission related jitter, a remultiplexer regenerates a local clock for each selected program in the multiplex. Comparing the local clock with the PCR of the incoming stream and number of bytes received since last PCR values, the remultiplexer can find the variation in PCR values. If the absolute value of the jitter is greater than the pre-selected tolerance, the remultiplexer removes the jitter and replaces the PCR with an adjusted PCR. The remultiplexer readjusts DTS and PTS values according to the adjusted PCR value.

To meet the constraint in the above equation, it may be necessary to reduce the bitrate of some video elementary streams. This may be achieved by using a recoder. A recoder uncompresses a compressed stream and recompresses and re-encodes to meet the desired bitrate. Re-encoding, using previous encoding decisions passed from the decoder, will minimize picture quality degradation by simply re-quantizing. However, one may expect some degradation in picture quality with a reduction in bitrate.

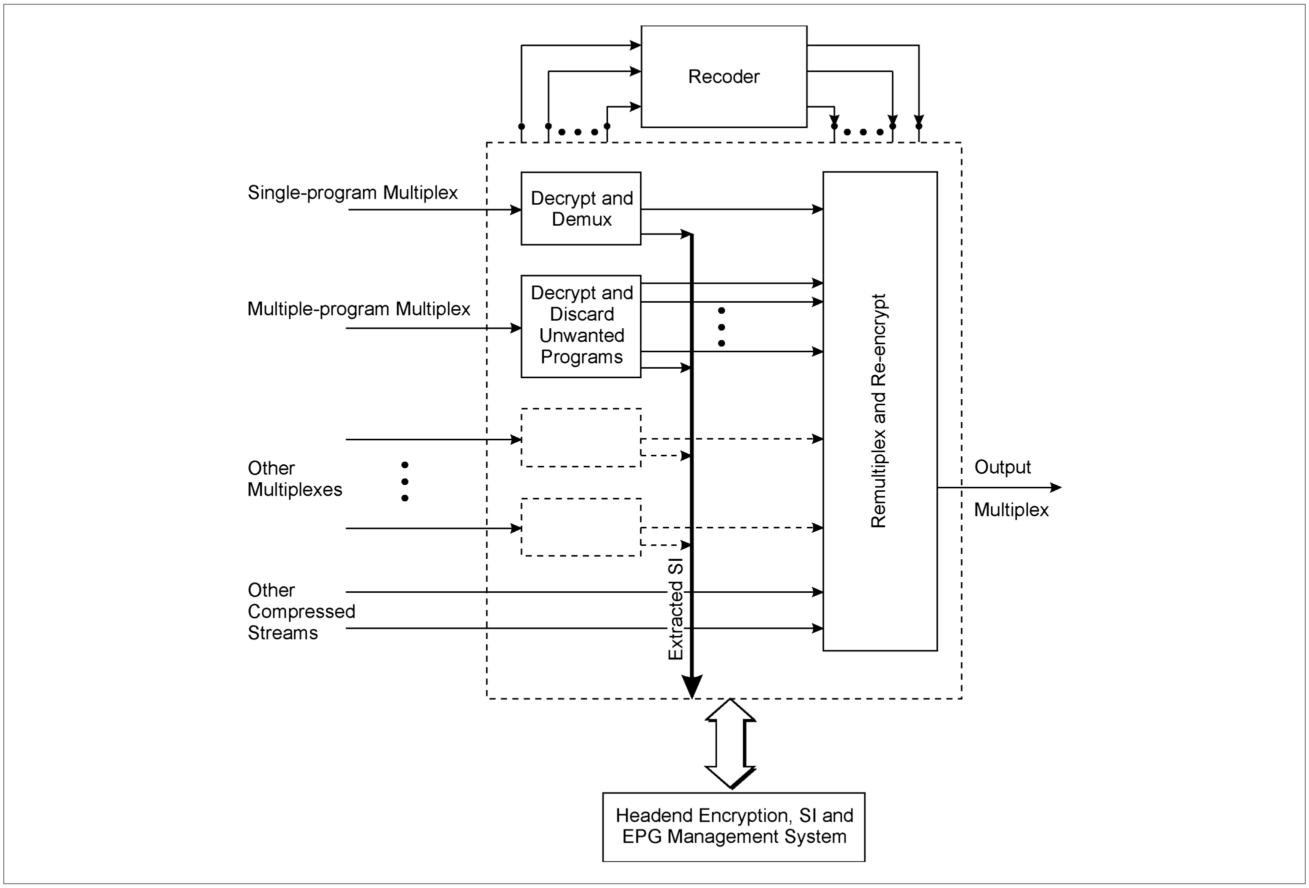

Figure 3. Simplified diagram of a remultiplexer

On occasion, it may be necessary to groom a program from a multiplex. For example, a network program has an overall bitrate of 19 Mbits/sec; 13 Mbits/sec provide actual program content (video and audio) and 6 Mbits/sec provide private data within the video PID or in a separate PID stream. This additional private data may be groomed and the recovered bandwidth may be used for other revenue-generating programs and services. A remultiplexer can simply filter data residing in a separate PID. If the data is not in a separate PID, external equipment may be needed to detect and remove such data.

Typically, a remultiplexer will have different input/output interface cards to accept signals from interfaces such as OC-3, DS-3, parallel and serial DVB, digital headend interface (DHEI), etc. Depending on the interface requirements and bitrates, several different sources may be used for the incoming multiplex streams.

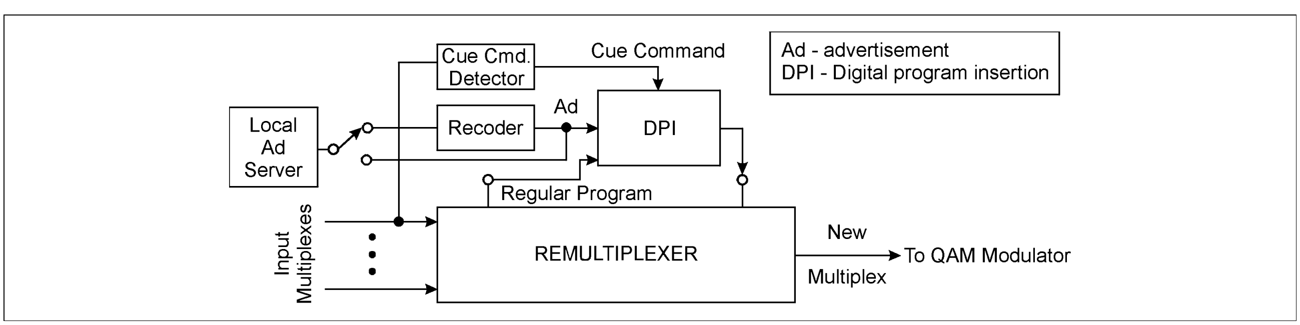

Figure 4. Local program/advertisement insertion

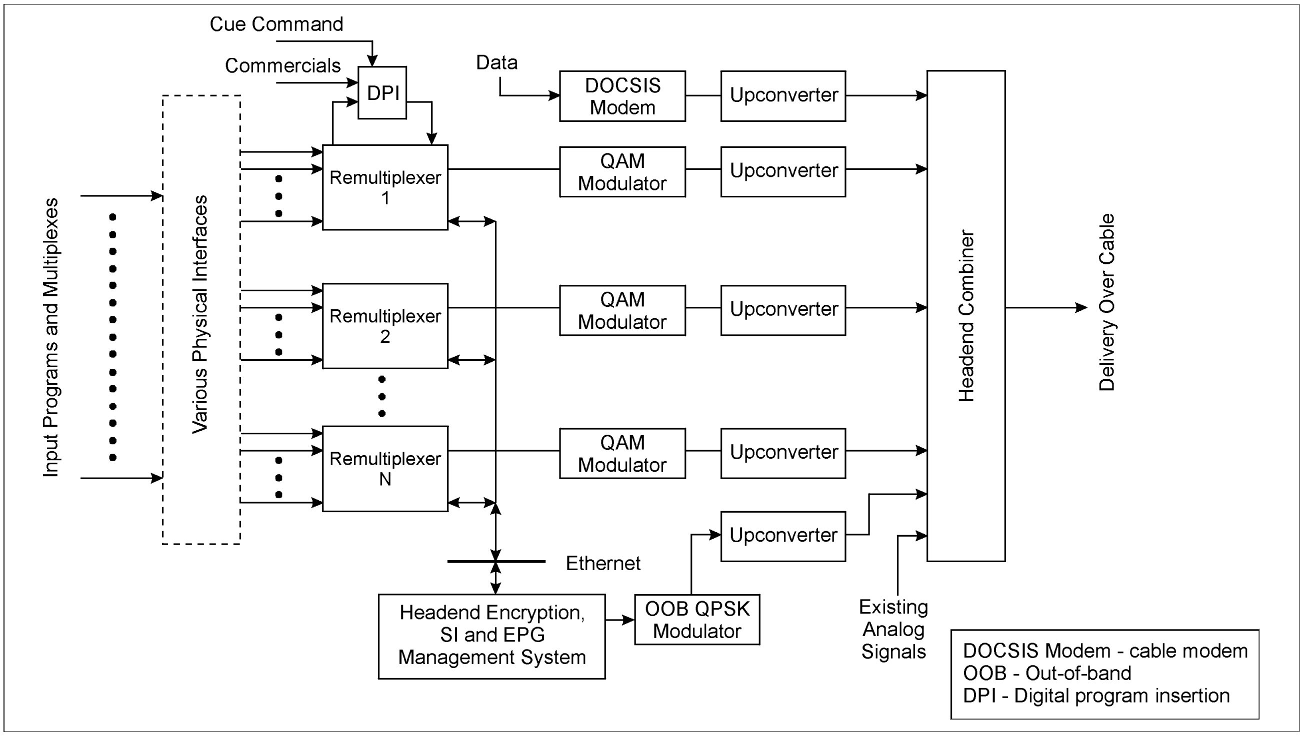

Figure 5. Headend architecture with analog and digital channels

PROGRAM INSERTION

Insertion of locally-generated commercials and short programs has become an integral part of the headend. First, revenue from local ads contributes significantly to overall cable revenue. Second, locally-generated civic and political short programs have become a necessity to local communities.

To insert commercials and short programs, a digital program insertion (DPI) system may be connected externally to a remultiplexer, as shown in Figure 4. A cue-command is detected from the input multiplex for one or more selected channels by a cue-command decoder. The latter output is fed to a DPI for start/stop signaling for an advertising insertion opportunity or avail. Locally-generated materials may be compressed at various bitrates using a non-real-time encoder and stored in a video server. This may be necessary to match the incoming channel bitrate. Alternatively, the material may be compressed at a higher bitrate. A real-time recoder may be used to reduce the bitrate to match the bitrate of the incoming program. The Society of Motion Pictures and Television Engineers (SMPTE) standard on splicing MPEG-2 transport streams includes cue commands (similar to existing analog cue-tones). Design of a cue-command decoder and DPI equipment based on this standard will be facilitated, but the actual insertion mechanism for switching compressed streams is not fully specified.

HEADEND ARCHITECTURE

The basic architecture of integrating digital signals with existing analog signals is shown in Figure 5. Digital multiplexers, carrying one or more programs, are input to a number of remultiplexers. It is possible that, due to some mismatch in interfaces between incoming signals and remultiplexer input interfaces, some hardware may be necessary to make input signals compatible with the remultiplexer input. As mentioned earlier, a remultiplexer will be an important piece of equipment in digital headends. It will be needed to select desired programs from the input multiplexes and to construct new packages (multiplexes) to be delivered over a single

6 MHz physical channel. The remultiplexer will need authorization for de-encrypting the selected channels. The channels, now in the clear, may be used for demultiplexing, recoding (if bitrate reduction is required), or digital program insertion before being remultiplexed in the new package for delivery over cable. The remultiplexer will also encrypt the elementary streams of the new multiplex. The new multiplexes will feed the QAM modulators. Each of these new multiplexes will modulate a 6 MHz carrier. The QAM-modulated carrier will be upconverted to one of the existing cable channels. All upconverted RF signals are combined with the RF analog channels in the headend channel combiner before being transmitted over cable networks.

As stated earlier, the remultiplexer will have authorization to decrypt the demultiplexed elementary streams. The remultiplexer will then extract program specific information (PSI) from the incoming multiplex and will send it to the headend management computer. An integrated program guide for all analog and digital channels can then be built from this information.

An integrated electronic program guide (EPG) is an interactive navigational tool that provides program content and schedule information. It supports selection of any analog or digital channel by direct entry of its channel number or symbolic name (call letters) on an on-screen display. Each of these channels is associated with a physical channel whose frequency range, modulation used, etc., should be known for correct tuning and demodulation. This information is part of the system or service information (SI). The SI is an extended version of PSI. PSI data provides information to enable automatic configuration of the receiver to demultiplex and decode the various program streams within the multiplex. EPG, along with SI, makes navigation of any channel user-transparent. This information is supplied on an out-of-band (OOB) channel. If any 8-VSB signal is transmitted using a cable service physical channel, and by-passes the set-top box (STB) to reach the DTV receiver, implementation of an integrated program guide could be complex. To implement an integrated program guide in a straightforward manner, the STB will demodulate and decode all signals passing through it. The TV will receive all signals and information through an interface, meaning that all digital signals must be QAM-modulated to be demodulated in the set-top box.

STATUS MONITORING

As mentioned earlier, digital technology has remarkable efficiency and flexibility. However, in some situations, it also presents complexity and challenges. One such area is the testing, measuring, and analyzing of DTV signals. First, the signal representation, transmission, and multiplexing characteristics of the DTV signal are quite different from analog TV signals. Second, the testing and measuring equipment currently available on the market, have not been standardized and have not matured. DTV signals may be tested in two parts—as modulated carrier signals and as demodulated baseband signals.

To test the signal quality of the digitally-modulated signal, a modulation analyzer is required. These analyzers provide constellation diagram, eye diagram pattern, error vector magnitude (EVM), and frequency response, from which channel gain, phase error, bit error rate (BER), noise-related problems, etc., can be found.

To test an RF-modulated signal, QAM or VSB analyzers are available from Hewlett-Packard, Tektronix, Applied Signal Technology, Wavetek, and others. At the baseband level, the transport baseband stream can be demultiplexed into component elementary streams. Each elementary stream can be analyzed using a tool like an MPEG-2 conformance verifier. In addition to checking syntax at various MPEG-2 layers, these tools can detect problems related to system information (PSI section), PCR, timing, jitter, and synchronization (PCR, PTS, DTS), and transport stream target decoder (TSTD) buffer overflow. To analyze signals at the baseband or elementary stream level, equipment for real-time monitoring and non-real-time analysis are available from Tektronix, HP, Sencore/Symbionics, Snell & Willcox, and others. Most equipment is PC-based and is somewhat different in terms of features and capabilities. Many software tools, including one from CableLabs, are also available for PC and UNIX platforms for non-real-time MPEG-2 conformance verification.

The noise in a digital video signal manifests itself differently than the noise in an analog signal/video. Any increase in noise will cause the analog signal picture quality to degrade gracefully. If the noise becomes severe and corrupts synchronization signals, the picture will be lost. An increase in noise in DTV signals will cause loss of margin, which in turn causes bit errors. If errored bits are part of MPEG-2 headers, such as sequence headers, picture headers, etc., effects may be visible in the entire picture (broken or blocky picture with irregular colors). On the other hand, if they are part of picture data, the effect may be very localized on-screen. One can expect reasonable video quality up to a certain threshold in signal-to-noise ratio (SNR). If this ratio falls below the threshold level, the noise will be so severe that the video will appear totally unrecognizable and the decoder will fail. Therefore, the signal fidelity in both modulated and baseband domains at the headend will help maintain satisfactory performance to the subscriber.

CONCLUSION

Various forms of digital television signals, headend interfaces, and signal processing requirements have been discussed. Important characteristics of each signal type have been described. A brief overview of each step handling incoming digital signals and downstream processing have been explained. A conceptual architecture has been presented to show how new digital equipment may be integrated, along with the existing analog components, to make the headend a complete program delivery system for both analog and digital channels. The signal and noise characteristics of the incoming DTV signals, as well as methods to test and monitor them, have been discussed. Continuous monitoring of the integrity and quality of the incoming signals will ensure proper signal quality. The equipment and the software from several manufacturers to test, measure, and analyze these signals are becoming available.

All the equipment mentioned above is not required to add digital capability to an existing analog headend. For example, DPI systems and recoders are not required for delivery of digital signals and may be added incrementally as deemed necessary. DPI is of less significance to pay-per-view (PPV) channels. Optional test and measurement equipment supports reliable operation through status monitoring. Also, the equipment needed is proportional to the number of digital channels allocated in the available system bandwidth.

In summary, digital television network interfaces will provide greatly improved capacity, flexibility, and quality to existing analog offerings. Several new interface considerations and requirements presented here will be needed for successfully integrating and distributing these new services.

ACKNOWLEDGMENTS

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