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Digital Broadcast Technologies

Date: Aug 20, 2001 By Michael Adams. Article is provided courtesy of Cisco Press.

Digital technology is becoming pervasive in all types of services. As computing power continues to increase, more and more functions can be tackled in the digital domain. An excellent example is the transmission of television pictures. This sample chapter from OpenCable™ Architecture, winner of NCTA Book of the Year Award, introduces a number of key digital broadcast technologies.

Digital technology is becoming pervasive in all types of services. As computing power continues to increase according to Moore's Law (see Chapter 1, "Why Digital Television?"), more and more functions can be tackled in the digital domain. An excellent example is the transmission of television pictures.

Nevertheless, digital technology is not a panacea. The complexity of the techniques can introduce reliability and quality issues. In addition, only a few engineers thoroughly understand all these techniques, making us more reliant on a smaller number of *de facto* standard chip-sets.

This chapter introduces a number of key digital technologies. If you are familiar with these technologies, you might want to skim through or skip over this chapter. There are many excellent texts (see the list of references at the end of the chapter) that explain how these digital technologies work. This chapter does not attempt to repeat them, but instead provides a commentary on why these techniques are so important and what they mean in practical terms. This chapter discusses

- Video compression—The basic principles of the video compression algorithms commonly used for entertainment quality video, the importance of choosing the correct parameters for video encoding, and some alternative video compression algorithms.
- Audio compression—The basic principles of MPEG-2 audio compression and Dolby AC-3 audio compression.
- Data—Arbitrary *private* data can be carried by the underlying layers.
- System information—Tabular data format used by the digital receiver device to drive content navigation, tuning, and presentation.
- Timing and synchronization—A mechanism is required to recover the source timing at the decoder so that the presentation layer can synchronize the various components and display them at exactly the intended rate.
- Packetization—The segmentation and encapsulation of elementary data streams into transport packets.
- Multiplexing—The combining of transport streams containing audio, video, data, and system information.
- Baseband transmission—The various mechanisms for carrying digital transport streams: the Digital Video Broadcast (DVB) asynchronous serial interface (ASI), Synchronous Optical Networks (SONET), Asynchronous Transfer Mode (ATM), and Internet Protocol (IP).
- Broadband transmission—The digital transmission payload must be modulated before it can be delivered by an analog cable system. Quadrature Amplitude Modulation (QAM) has been selected as the best modulation for *downstream* transmission in cable systems. Other modulation techniques include quaternary phase shift keying (QPSK) and vestigial side band (VSB) modulation.

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in-band communications stack for a digital cable set-top and is discussed in Chapter 6, "The Digital Set-Top Converter," in more detail.

Figure 4-1 Layered Model for Digital Television

Video Compression

Image compression has been around for some time but video compression is relatively new. The processing requirements to compress even a single frame of video are large—to compress 30 frames (or 60 fields) per second of video requires massive processing power (delivered by rapid advances in semiconductor technology).

Nonetheless, digital video must be compressed before it can be transmitted over a cable system. Although other compression algorithms exist, the dominant standard for video compression is MPEG-2 (from Moving Picture Experts Group). Although MPEG-2 video compression was first introduced in 1993, it is now firmly established and provides excellent results in cable, satellite, terrestrial broadcast, and digital versatile disk (DVD) applications.

This section discusses

- MPEG-2 video compression—The basics of the MPEG-2 video compression algorithm and why it has become the dominant standard for entertainment-video compression
- Other video compression algorithms—Why other video compression algorithms have their applications and why they are unlikely to challenge MPEG-2 video compression in the entertainment world for some time
- Details on MPEG-2 video compression—Some more details on the use of MPEG-2 video compression and its parameters

MPEG-2 Compression

MPEG-2 video compression is the *de facto* standard for entertainment video. MPEG-2 video compression is popular for a number of reasons:

- It is an international standard [ISO/IEC IS 13818-2].
- MPEG-2 places no restrictions on the video encoder implementation. This allows each encoder designer to introduce new techniques to improve compression efficiency and picture quality. Since MPEG-2 video encoders were first introduced in 1993, compression efficiency has improved by 30 to 40%, despite predictions by many that MPEG-2's fundamental theoretical limitations would prevent this.
- MPEG-2 fully defines the video decoder's capability at particular levels and profiles. Many MPEG-2 chip-sets are available and will work with any *main level at main profile (MP@ML)*–compliant MPEG-2 bit-stream from any source. Nevertheless, quality can change significantly from one MPEG-2 video decoder to another, especially in error handling and video clip transitions.
- MPEG-2 video compression is part of a larger standard that includes support for transport and timing functions.

Moreover, MPEG-2 is likely to remain as the dominant standard for entertainment video because it has been so successful in establishing an inventory of standard decoders (both in existing consumer electronics products and in the chip libraries of most large semiconductor companies). Additional momentum comes from the quantity of real-time and stored content already compressed into MPEG-2 format. Even succeeding work by the MPEG committees has been abandoned (MPEG-3) or retargeted to solve different problems (MPEG-4 and MPEG-7).

MPEG-2 is a *lossy* video compression method based on motion vector estimation, discrete cosine transforms, quantization, and Huffman encoding. (*Lossy* means that data is lost, or thrown away, during compression, so quality after decoding is less than the original picture.) Taking these techniques in order:

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frames, in the form of best approximations of each part of a frame as a translation (generally due to motion) of a similar-sized piece of another video frame. Essentially, there is a lot of *temporal redundancy* in video, which can be discarded. (The term *temporal redundancy* is applied to information that is repeated from one frame to another.)

- *Discrete cosine transform (DCT)* is used to convert spatial information into frequency information. This allows the encoder to discard information, corresponding to higher video frequencies, which are less visible to the human eye.
- *Quantization* is applied to the DCT coefficients of either original frames (in some cases) or the DCT of the residual (after motion estimation) to restrict the set of possible values transmitted by placing them into groups of values that are almost the same.
- *Huffman encoding* uses short codes to describe common values and longer codes to describe rarer values—this is a type of *entropy coding*.

The foregoing is a highly compressed summary of MPEG-2 video compression (with many details omitted). However, there are so many excellent descriptions of MPEG compression (see *DTV: The Revolution in Electronic Imaging*, by Jerry C. Whitaker; *Digital Compression for Multimedia: Principles and Standards*, by Jerry D. Gibson and others; *Testing Digital Video*, by Dragos Ruiu and others; and *Modern Cable Television Technology; Video, Voice, and Data Communications,* by Walter Ciciora and others) that more description is not justified here. Instead, the following sections concentrate on the most interesting aspects of MPEG:

- What are MPEG-2's limitations?
- What happens when MPEG-2 breaks?
- How can compression ratios be optimized to reduce transmission cost without compromising (too much) on quality?

MPEG Limitations

If MPEG-2 is so perfect, why is there any need for other compression schemes? (There are a great many alternative compression algorithms, such as wavelet, pyramid, fractal, and so on.) MPEG-2 is a good solution for coding relatively high-quality video when certain transmission requirements can be met. However, MPEG-2 coding is rarely used in Internet applications because the Internet cannot generally guarantee the quality of service (QoS) parameters required for MPEG-2–coded streams. These QoS parameters are summarized in Table 4-1.

Table 4-1 *MPEG-2 QoS Parameters for Entertainment Quality Video*

MPEG-2 QoS Parameters for Entertainment Quality Video

Bit Rate	1.5–20 Mbps Constant or Variable Bit Rate (CBR or VBR)
Bit error rate (BER)	Less than 1 in 10^{-10}
Packet/cell loss rate	Less than 1 in 10^{-8}
Packet/cell delay variation	Less than 500 nS

As you can see from the table, for entertainment-quality video, MPEG-2 typically requires a reasonably high bit rate, and this bit rate must be guaranteed. Video-coding will, in general, produce a variable information rate, but MPEG-2 allows for CBR transmission facilities (for example, satellite transponders, microwave links, and fiber transmission facilities). As such, MPEG-2 encoders attempt to take advantage of every bit in the transmission link by coding extra detail during less-challenging scenes. When the going gets tough—during a car chase, for example—MPEG-2 encoders use more bits for motion and transmit less detail. Another way to think of this is that MPEG-2 encoding varies its degree of loss according to the source material. Fortunately, the human visual system tends to work in a similar way, and we pay

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whether you are watching it or you are in it!)

MPEG-2 coded material is extremely sensitive to errors and lost information because of the way in which MPEG-2 puts certain vital information into a single packet. If this packet is lost or corrupted, there can be a significant impact on the decoder, causing it to drop frames or to produce very noticeable blocking artifacts. If you think of an MPEG-2 stream as a list of instructions to the decoder, you can understand why the corruption of a single instruction can play havoc with the decoded picture.

Finally, MPEG-2 is extremely sensitive to variations in transmission delay. These are not usually measurable in synchronous transmission systems (for example, satellite links) because each bit propagates through the system according to the clock rate. In packet- or cell-based networks, however, it is possible for each packet-sized group of bits to experience a different delay. MPEG-2 was designed with synchronous transmission links in mind and embeds timing information into certain packets by means of timestamps. If the timestamps experience significant *jitter* (or cell delay variation), it causes distortions in audio and video fidelity due to timing variations in the sample clocks—for example, color shifts due to color subcarrier phase variations.

MPEG-2 Artifacts

What are MPEG artifacts? In practice, all lossy encoders generate *artifacts,* or areas of unfaithful visual reproduction, all the time; if the encoder is well designed, all these artifacts will be invisible to the human eye. However, the best laid plans sometimes fail; the following are some of the more common MPEG-2 artifacts:

- If the compression ratio is too high, there are sometimes simply not enough bits to encode the video signal without significant loss. The better encoders will progressively *soften* the picture (by discarding some picture detail); however, poorer encoders sometimes break down and overflow an internal buffer. When this happens, all kinds of visual symptoms—from bright green blocks to dropped frames—can result. After such a *breakdown*, the encoder will usually recover for a short period until once again the information rate gets too high to code into the available number of bits.

- Another common visible artifact is sometimes visible in dark scenes or in close-ups of the face and is sometimes called *contouring*. As the name suggests, the image looks a little like a contour map drawn with a limited set of shades rather than a continuously varying palette. This artifact sometimes reveals the macro-block boundaries (which is sometimes called *tiling*). When this happens, it is usually because the encoder allocates too few quantization levels to the scene.

  NOTE

  Macro-blocks are areas of 16-by-16 pixels that are used by MPEG for DCT and motion-estimation purposes. See Chapter 3 of *Modern Cable Television Technology; Video, Voice, and Data Communications* by Walter Ciciora and others, for more details.

- High-frequency *mosquito* noise will sometimes be apparent in the background. Mosquito noise is often apparent in surfaces, such as wood, plaster, and wool, that contain an almost limitless amount of detail due to their natural texture. The encoder can be overtaxed by so much detail and creates a visual effect that looks as if the walls are crawling with ants.

There are many more artifacts associated with MPEG encoding and decoding; however, a well-designed system should rarely, if ever, produce annoying visible artifacts.

MPEG-2 Operating Guidelines

To avoid visible artifacts due to encoding, transmission errors, and decoding, the entire MPEG-2 system must be carefully designed to operate within certain guidelines:

- The compression ratio cannot be pushed too high. Just where the limit is on

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engineers and artists and will vary according to encoder performance (there is some expectation of improvements in rate with time, although also some expectation of a law of diminishing returns). Table 4-2 gives some guidance based on experience.

Table 4-2 *MPEG-2 Resolution Versus Minimum Bit Rate Guidelines*

Material	Resolution	Minimum Bit Rate (CBR)
Movies	360 x 240 (CIF)	1.5 Mbps
Movies	360 x 480 (half)	2 Mbps
Movies	540 x 480 (3/4)	3 Mbps
Movies	720 x 480 (full)	4 Mbps
Sports (video)	540 x 480 (3/4)	5 Mbps
Sports (video)	720 x 480 (full)	6 Mbps

- The transmission system must generate very few errors during the average viewing time of an event. For example, in a two-hour movie, the same viewers may tolerate very few significant artifacts (such as frame drop or green blocks). In practice, this means that the transmission system must employ forward error correction (FEC) techniques.

Other Video Compression Algorithms

There are a great many alternative video compression algorithms, such as wavelet, pyramid, fractal, and so on (see Chapter 7 of *Digital Compression for Multimedia: Principles and Standards* by Jerry D. Gibson and others). Many have special characteristics that make them suitable for very low bit rate facilities, for software decoding on a PC, and so on. However, it is unlikely that they will pose a significant threat to MPEG-2 encoding for entertainment video in the near future.

Compression Processing Requirements

Let's take a full-resolution video frame that contains 480 lines, each consisting of 720 pixels. The total frame, therefore, contains 345,600 pixels. Remember that a new frame arrives from the picture source every 33 milliseconds. Thus, the pixel rate is 10,368,000 per second. Imagine that the compression process requires about 100 operations per pixel. Obviously, a processor with a performance of 1,000 million instructions per second (mips) is required.

In practice, custom processing blocks are often built in hardware to handle common operations, such as motion estimation and DCT used by MPEG-2 video compression.

Details of MPEG-2 Video Compression

The following sections detail some of the more practical aspects of MPEG-2 video compression:

- Picture resolution—MPEG-2 is designed to handle the multiple picture resolutions that are commonly in use for broadcast television. This section defines what is meant by picture resolution and how it affects the compression process.
- Compression ratio—MPEG-2 can achieve excellent compression ratios when compared to analog transmission, but there is some confusion about the definition of compression ratios. This section discusses the difference between the MPEG compression ratio and the overall compression ratio.
- Real-time MPEG-2 compression—Most of the programs delivered over cable systems are compressed in real-time at the time of transmission. This section discusses the special requirements for real-time MPEG-2 encoders.
- Non–real-time MPEG-2 compression—Stored-media content does not require a real-time encoder, and there are certain advantages to non–real-time compression systems.

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