

# Digital Audio Compression

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## Abstract

*Compared to most digital data types, with the exception of digital video, the data rates associated with uncompressed digital audio are substantial. Digital audio compression enables more efficient storage and transmission of audio data. The many forms of audio compression techniques offer a range of encoder and decoder complexity, compressed audio quality, and differing amounts of data compression. The  $\mu$ -law transformation and ADPCM coder are simple approaches with low-complexity, low-compression, and medium audio quality algorithms. The MPEG/audio standard is a high-complexity, high-compression, and high audio quality algorithm. These techniques apply to general audio signals and are not specifically tuned for speech signals.*

## Introduction

Digital audio compression allows the efficient storage and transmission of audio data. The various audio compression techniques offer different levels of complexity, compressed audio quality, and amount of data compression.

This paper is a survey of techniques used to compress digital audio signals. Its intent is to provide useful information for readers of all levels of experience with digital audio processing. The paper

begins with a summary of the basic audio digitization process. The next two sections present detailed descriptions of two relatively simple approaches to audio compression:  $\mu$ -law and adaptive differential pulse code modulation. In the following section, the paper gives an overview of a third, much more sophisticated, compression audio algorithm from the Motion Picture Experts Group. The topics covered in this section are quite complex and are intended for the reader who is familiar with digital signal processing. The paper concludes with a discussion of software-only real-time implementations.

## Digital Audio Data

The digital representation of audio data offers many advantages: high noise immunity, stability, and reproducibility. Audio in digital form also allows the efficient implementation of many audio processing functions (e.g., mixing, filtering, and equalization) through the digital computer.

The conversion from the analog to the digital domain begins by sampling the audio input in regular, discrete intervals of time and quantizing the sampled values into a discrete number of evenly spaced levels. The digital audio data consists of a sequence of binary values representing the number of quantizer levels for each audio sample. The method of representing each sample with an independent code word is called pulse code modulation (PCM). Figure 1 shows the digital audio process.

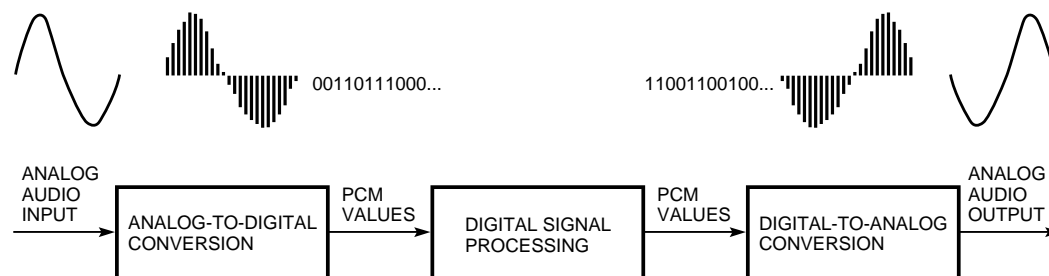


Figure 1 Digital Audio Process

According to the Nyquist theory, a time-sampled signal can faithfully represent signals up to half the sampling rate.[1] Typical sampling rates range from 8 kilohertz (kHz) to 48 kHz. The 8-kHz rate covers a frequency range up to 4 kHz and so covers most of the frequencies produced by the human voice. The 48-kHz rate covers a frequency range up to 24 kHz and more than adequately covers the entire audible frequency range, which for humans typically extends to only 20 kHz. In practice, the frequency range is somewhat less than half the sampling rate because of the practical system limitations.

The number of quantizer levels is typically a power of 2 to make full use of a fixed number of bits per audio sample to represent the quantized values. With uniform quantizer step spacing, each additional bit has the potential of increasing the signal-to-noise ratio, or equivalently the dynamic range, of the quantized amplitude by roughly 6 decibels (dB). The typical number of bits per sample used for digital audio ranges from 8 to 16. The dynamic range capability of these representations thus ranges from 48 to 96 dB, respectively. To put these ranges into perspective, if 0 dB represents the weakest audible sound pressure level, then 25 dB is the minimum noise level in a typical recording studio, 35 dB is the noise level inside a quiet home, and 120 dB is the loudest level before discomfort begins.[2] In terms of audio perception, 1 dB is the minimum audible change in sound pressure level under the best conditions, and doubling the sound pressure level amounts to one perceptual step in loudness.

Compared to most digital data types (digital video excluded), the data rates associated with uncompressed digital audio are substantial. For example, the audio data on a compact disc (2 channels of audio sampled at 44.1 kHz with 16 bits per sample) requires a data rate of about 1.4 megabits per second. There is a clear need for some form of compression to enable the more efficient storage and transmission of this data.

The many forms of audio compression techniques differ in the trade-offs between encoder and decoder complexity, the compressed audio quality, and the amount of data compression. The techniques presented in the following sections of this paper cover the full range from the  $\mu$ -law, a low-complexity, low-compression, and medium audio quality algorithm, to MPEG/audio, a high-complexity, high-compression, and high audio quality algorithm. These techniques apply to general audio signals and are not specifically tuned for speech signals. This paper does not cover audio compression algorithms designed specifically for speech signals. These algorithms are generally based on a modeling of the vocal tract and do not work well for nonspeech audio

signals.[3,4] The federal standards 1015 LPC (linear predictive coding) and 1016 CELP (coded excited linear prediction) fall into this category of audio compression.

### $\mu$ -law Audio Compression

The  $\mu$ -law transformation is a basic audio compression technique specified by the Comité Consultatif Internationale de Télégraphique et Téléphonique (CCITT) Recommendation G.711.[5] The transformation is essentially logarithmic in nature and allows the 8 bits per sample output codes to cover a dynamic range equivalent to 14 bits of linearly quantized values. This transformation offers a compression ratio of (number of bits per source sample) / 8 to 1. Unlike linear quantization, the logarithmic step spacings represent low-amplitude audio samples with greater accuracy than higher-amplitude values. Thus the signal-to-noise ratio of the transformed output is more uniform over the range of amplitudes of the input signal. The  $\mu$ -law transformation is

$$y = \begin{cases} 255 - \frac{127}{\ln(1+\mu)} \times \ln(1 + \mu|x|) & \text{for } x \geq 0 \\ 127 - \frac{127}{\ln(1+\mu)} \times \ln(1 + \mu|x|) & \text{for } x < 0 \end{cases}$$

where  $m = 255$ , and  $x$  is the value of the input signal normalized to have a maximum value of 1. The CCITT Recommendation G.711 also specifies a similar A-law transformation. The  $\mu$ -law transformation is in common use in North America and Japan for the Integrated Services Digital Network (ISDN) 8-kHz-sampled, voice-grade, digital telephony service, and the A-law transformation is used elsewhere for the ISDN telephony.

### Adaptive Differential Pulse Code Modulation

Figure 2 shows a simplified block diagram of an adaptive differential pulse code modulation (ADPCM) coder.[6] For the sake of clarity, the figure omits details such as bit-stream formatting, the possible use of side information, and the adaptation blocks. The ADPCM coder takes advantage of the fact that neighboring audio samples are generally similar to each other. Instead of representing each audio sample independently as in PCM, an ADPCM encoder computes the difference between each audio sample and its predicted value and outputs the PCM value of the differential. Note that the ADPCM *encoder* (Figure 2a) uses most of the components of the ADPCM *decoder* (Figure 2b) to compute the predicted values.

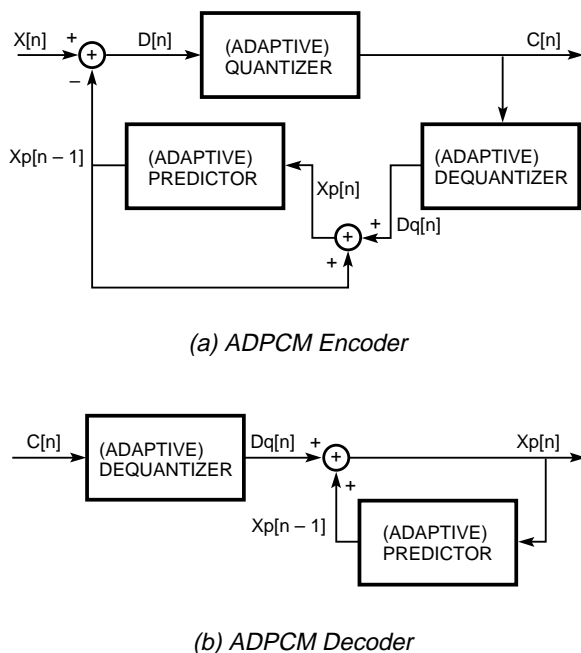


Figure 2 ADPCM Compression and Decompression

The quantizer output is generally only a (signed) representation of the number of quantizer levels. The requantizer reconstructs the value of the quantized sample by multiplying the number of quantizer levels by the quantizer step size and possibly adding an offset of half a step size. Depending on the quantizer implementation, this offset may be necessary to center the requantized value between the quantization thresholds.

The ADPCM coder can adapt to the characteristics of the audio signal by changing the step size of either the quantizer or the predictor, or by changing both. The method of computing the predicted value and the way the predictor and the quantizer adapt to the audio signal vary among different ADPCM coding systems.

Some ADPCM systems require the encoder to provide side information with the differential PCM values. This side information can serve two purposes. First, in some ADPCM schemes the decoder needs the additional information to determine either the predictor or the quantizer step size, or both. Second, the data can provide redundant contextual information to the decoder to enable recovery from errors in the bit stream or to allow random access entry into the coded bit stream.

The following section describes the ADPCM algorithm proposed by the Interactive Multimedia Association (IMA). This algorithm offers a compression factor of (number of bits per source sample)/4 to 1. Other ADPCM audio compression schemes include the CCITT Recommendation G.721 (32 kilobits per second compressed data rate) and Recommendation G.723 (24 kilobits per second compressed data rate) standards and the compact disc interactive audio compression algorithm.[7,8]

*The IMA ADPCM Algorithm.* The IMA is a consortium of computer hardware and software vendors cooperating to develop a de facto standard for computer multimedia data. The IMA's goal for its audio compression proposal was to select a public-domain audio compression algorithm able to provide good compressed audio quality with good data compression performance. In addition, the algorithm had to be simple enough to enable software-only, real-time decompression of stereo, 44.1-kHz-sampled, audio signals on a 20-megahertz (MHz) 386-class computer. The selected ADPCM algorithm not only meets these goals, but is also simple enough to enable software-only, real-time encoding on the same computer.

The simplicity of the IMA ADPCM proposal lies in the crudity of its predictor. The predicted value of the audio sample is simply the decoded value of the immediately previous audio sample. Thus the predictor block in Figure 2 is merely a time-delay element whose output is the input delayed by one audio sample interval. Since this predictor is not adaptive, side information is not necessary for the reconstruction of the predictor.

Figure 3 shows a block diagram of the quantization process used by the IMA algorithm. The quantizer outputs four bits representing the signed magnitude of the number of quantizer levels for each input sample.

Adaptation to the audio signal takes place only in the quantizer block. The quantizer adapts the step size based on the current step size and the quantizer output of the immediately previous input. This adaptation can be done as a sequence of two table lookups. The three bits representing the number of quantizer levels serve as an index into the first table lookup whose output is an index adjustment for the second table lookup. This adjustment is added to a stored index value, and the range-limited result is used as the index to the second table lookup. The summed index value is stored for use in the next iteration of the step-size adaptation. The output of the second table lookup is the new quantizer step size. Note that given a starting value for the index into the second table lookup, the data used for adaptation is completely deducible from the quantizer outputs; side information is not required for the quantizer adaptation. Figure 4 illustrates a block diagram of the step-size adaptation process, and Tables 1 and 2 provide the table lookup contents.

**Table 1**  
**First Table Lookup for the IMA**  
**ADPCM Quantizer Adaptation**

Three Bits Quantized Magnitude	Index Adjustment
000	-1
001	-1
010	-1
011	-1
100	2
101	4
110	6
111	8

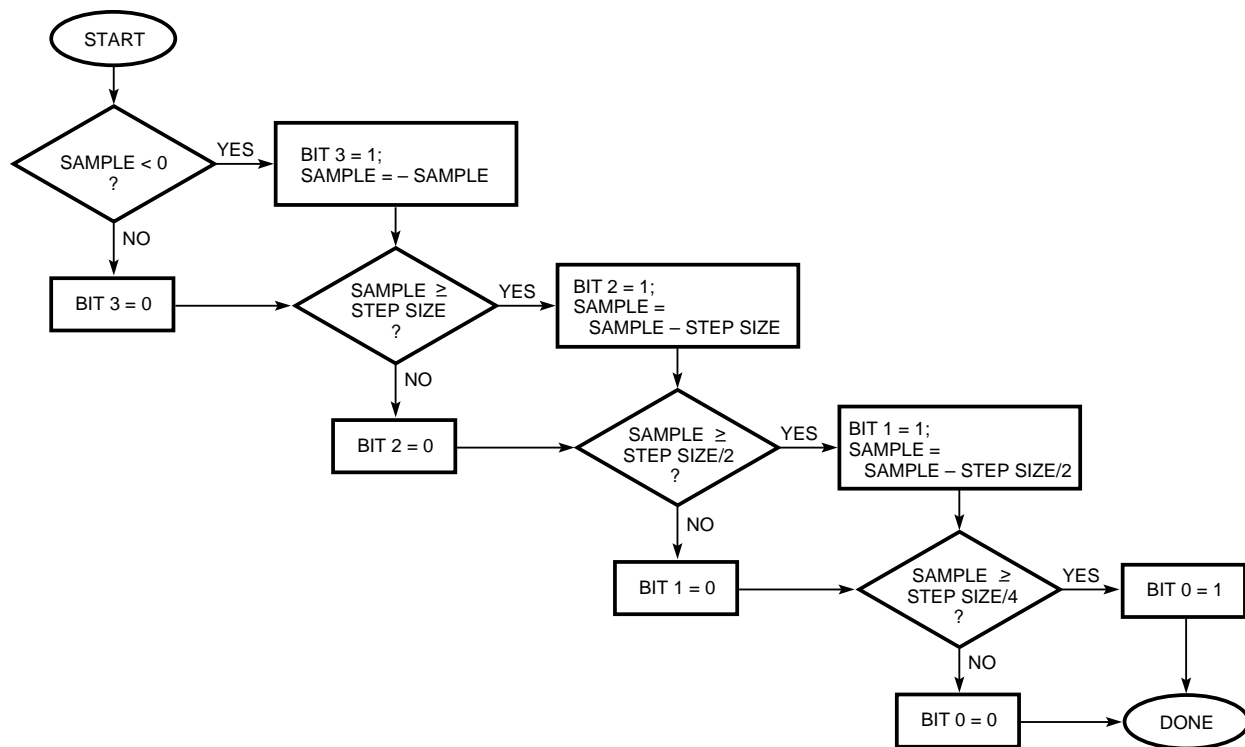


Figure 3 IMA ADPCM Quantization

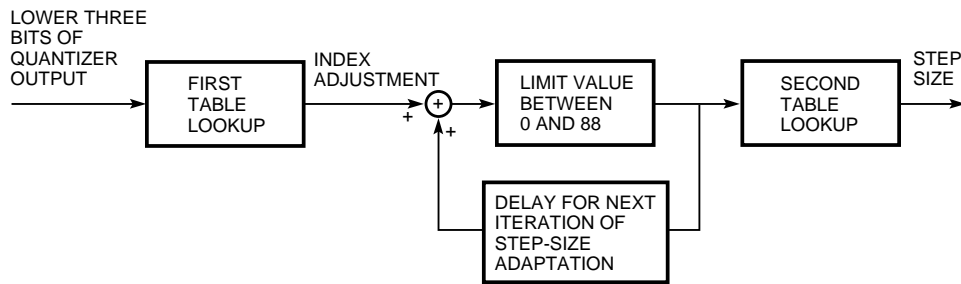


Figure 4 IMA ADPCM Step-size Adaptation

**Table 2**  
**Second Table Lookup for the IMA ADPCM Quantizer Adaptation**

Index	Step Size	Index	Step Size	Index	Step Size	Index	Step Size
0	7	22	60	44	494	66	4,026
1	8	23	66	45	544	67	4,428
2	9	24	73	46	598	68	4,871
3	10	25	80	47	658	69	5,358
4	11	26	88	48	724	70	5,894
5	12	27	97	49	796	71	6,484
6	13	28	107	50	876	72	7,132
7	14	29	118	51	963	73	7,845
8	16	30	130	52	1,060	74	8,630
9	17	31	143	53	1,166	75	9,493
10	19	32	157	54	1,282	76	10,442
11	21	33	173	55	1,411	77	11,487
12	23	34	190	56	1,552	78	12,635
13	25	35	209	57	1,707	79	13,899
14	28	36	230	58	1,878	80	15,289
15	31	37	253	59	2,066	81	16,818
16	34	38	279	60	2,272	82	18,500
17	37	39	307	61	2,499	83	20,350
18	41	40	337	62	2,749	84	22,358
19	45	41	371	63	3,024	85	24,623
20	50	42	408	64	3,327	86	27,086
21	55	43	449	65	3,660	87	29,794
						88	32,767

**IMA ADPCM: Error Recovery.** A fortunate side effect of the design of this ADPCM scheme is that decoder errors caused by isolated code word errors or edits, splices, or random access of the compressed bit stream generally do not have a disastrous impact on decoder output. This is usually not true for compression schemes that use prediction. Since prediction relies on the correct decoding of previous audio samples, errors in the decoder tend to propagate. The next section explains why the error propagation is generally limited and not disastrous for the IMA algorithm. The decoder reconstructs the audio sample,  $Xp[n]$ , by adding the previously decoded audio sample,  $Xp[n-1]$  to the result of a signed magnitude product of the code word,  $C[n]$ , and the quantizer step size plus an offset of one-half step size:

$$Xp[n] = Xp[n-1] + \text{step\_size}[n] \times C'[n]$$

where  $C'[n]$  = one-half plus a suitable numeric conversion of  $C[n]$ .

An analysis of the second step-size table lookup reveals that each successive entry is about 1.1 times the previous entry. As long as range limiting of the second table index does not take place, the value for  $\text{step\_size}[n]$  is approximately the product of the previous value,  $\text{step\_size}[n-1]$ , and a function of the code word,  $F(C[n-1])$ :

$$\text{step\_size}[n] = \text{step\_size}[n-1] \times F(C[n-1])$$

The above two equations can be manipulated to express the decoded audio sample,  $Xp[n]$ , as a function of the step size and the decoded sample value at time,  $m$ , and the set of code words between time,  $m$ , and  $n$

$$Xp[n] = Xp[m] + \text{step\_size}[m] \times \sum_{i=m+1}^n \left\{ \prod_{j=m+1}^i F(C[j]) \right\} \times C'[i]$$

Note that the terms in the summation are only a function of the code words from time  $m+1$  onward. An error in the code word,  $C[q]$ , or a random access entry into the bit stream at time  $q$  can result in an error in the decoded output,  $Xp[q]$ , and the quantizer step size,  $\text{step\_size}[q+1]$ . The above equation shows that an error in  $Xp[m]$  amounts to a constant offset to future values of  $Xp[n]$ . This offset is inaudible unless the decoded output exceeds its permissible range and is clipped. Clipping results in a momentary audible distortion but also serves to correct partially or fully the offset term. Furthermore, digital high-pass filtering of the decoder output can remove this constant offset term. The above equation also shows that an error in  $\text{step\_size}[m+1]$  amounts to an unwanted gain or attenuation of future values of the decoded output  $Xp[n]$ . The shape

of the output wave form is unchanged unless the index to the second step-size table lookup is range limited. Range limiting results in a partial or full correction to the value of the step size.

The nature of the step-size adaptation limits the impact of an error in the step size. Note that an error in  $\text{step\_size}[m+1]$  caused by an error in a single code word can be at most a change of  $(1.1)^9$ , or 7.45 dB in the value of the step size. Note also that any sequence of 88 code words that all have magnitude 3 or less (refer to Table 1) completely corrects the step size to its minimum value. Even at the lowest audio sampling rate typically used, 8 kHz, 88 samples correspond to 11 milliseconds of audio. Thus random access entry or edit points exist whenever 11 milliseconds of low-level signal occur in the audio stream.

## MPEG/Audio Compression

The Motion Picture Experts Group (MPEG) audio compression algorithm is an International Organization for Standardization (ISO) standard for high-fidelity audio compression. It is one part of a three-part compression standard. With the other two parts, video and systems, the composite standard addresses the compression of synchronized video and audio at a total bit rate of roughly 1.5 megabits per second.

Like  $\mu$ -law and ADPCM, the MPEG/audio compression is lossy; however, the MPEG algorithm can achieve transparent, perceptually lossless compression. The MPEG/audio committee conducted extensive subjective listening tests during the development of the standard. The tests showed that even with a 6-to-1 compression ratio (stereo, 16-bit-per-sample audio sampled at 48 kHz compressed to 256 kilobits per second) and under optimal listening conditions, expert listeners were unable to distinguish between coded and original audio clips with statistical significance. Furthermore, these clips were specially chosen because they are difficult to compress. Grewin and Ryden give the details of the setup, procedures, and results of these tests.[9]

The high performance of this compression algorithm is due to the exploitation of auditory masking. This masking is a perceptual weakness of the ear that occurs whenever the presence of a strong audio signal makes a spectral neighborhood of weaker audio signals imperceptible. This noise-masking phenomenon has been observed and corroborated through a variety of psychoacoustic experiments.[10]



Empirical results also show that the ear has a limited frequency selectivity that varies in acuity from less than 100 Hz for the lowest audible frequencies to more than 4 kHz for the highest. Thus the audible spectrum can be partitioned into critical bands that reflect the resolving power of the ear as a function of frequency. Table 3 gives a listing of critical bandwidths.

Because of the ear's limited frequency resolving power, the threshold for noise masking at any given frequency is solely dependent on the signal activity within a critical band of that frequency. Figure 5 illustrates this property. For audio compression, this property can be capitalized by transforming the audio signal into the frequency domain, then dividing the resulting spectrum into subbands that approximate critical bands, and finally quantizing each subband according to the audibility of quantization noise within that band. For optimal compression, each band should be quantized with no more levels than necessary to make the quantization noise inaudible. The following sections present a more detailed description of the MPEG/audio algorithm.

#### *MPEG/Audio Encoding and Decoding*

Figure 6 shows block diagrams of the MPEG/audio encoder and decoder.[11,12] In this high-level representation, encoding closely parallels the process described above. The input audio stream passes through a filter bank that divides the input into multiple subbands. The input audio stream simultaneously passes through a psychoacoustic model that determines the signal-to-mask ratio of each subband. The bit or noise allocation block uses the signal-to-mask ratios to decide how to apportion the total number of code bits available for the quantization of the subband signals to minimize the audibility of the quantization noise. Finally, the last block takes the representation of the quantized audio samples and formats the data into a decodable bit stream. The decoder simply reverses the formatting, then reconstructs the quantized subband values, and finally transforms the set of subband values into a time-domain audio signal. As specified by the MPEG requirements, ancillary data not necessarily related to the audio stream can be fitted within the coded bit stream.

The MPEG/audio standard has three distinct layers for compression. Layer I forms the most basic algorithm, and Layers II and III are enhancements that use some elements found in Layer I. Each successive layer improves the compression performance but at the cost of greater encoder and decoder complexity.

*Layer I.* The Layer I algorithm uses the basic filter bank found in all layers. This filter bank divides the audio signal into 32 constant-width frequency bands. The filters are relatively simple and provide good time resolution with reasonable frequency resolution relative to the perceptual properties of the human ear. The design is a compromise with three notable concessions. First, the 32 constant-width bands do not accurately reflect the ear's critical bands. Figure 7 illustrates this discrepancy. The bandwidth is too wide for the lower frequencies so the number of quantizer bits cannot be specifically tuned for the noise sensitivity within each critical band. Instead, the included critical band with the greatest noise sensitivity dictates the number of quantization bits required for the entire filter band. Second, the filter bank and its inverse are not lossless transformations. Even without quantization, the inverse transformation would not perfectly recover the original input signal. Fortunately, the error introduced by the filter bank is small and inaudible. Finally, adjacent filter bands have a significant frequency overlap. A signal at a single frequency can affect two adjacent filter bank outputs.

**Table 3**  
**Approximate Critical Band Boundaries**

Band Number	Frequency (Hz) <sup>1</sup>	Band Number	Frequency (Hz) <sup>1</sup>
0	50	14	1,970
1	95	15	2,340
2	140	16	2,720
3	235	17	3,280
4	330	18	3,840
5	420	19	4,690
6	560	20	5,440
7	660	21	6,375
8	800	22	7,690
9	940	23	9,375
10	1,125	24	11,625
11	1,265	25	15,375
12	1,500	26	20,250
13	1,735		

<sup>1</sup>Frequencies are at the upper end of the band.

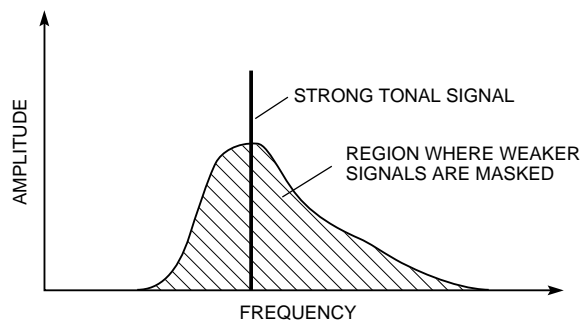
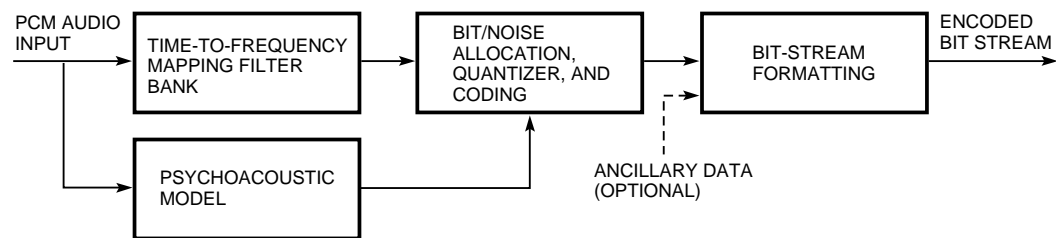
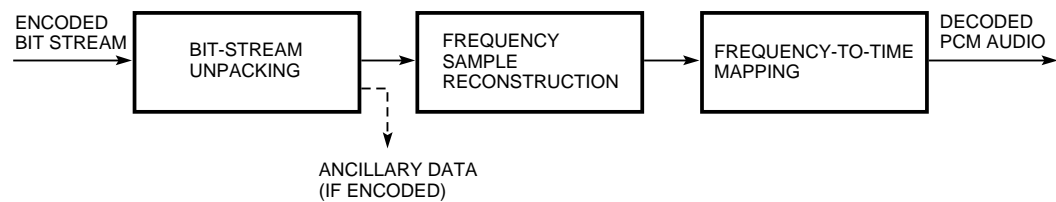


Figure 5 Audio Noise Masking



(a) MPEG/Audio Encoder



(b) MPEG/Audio Decoder

Figure 6 MPEG/Audio Compression and Decompression



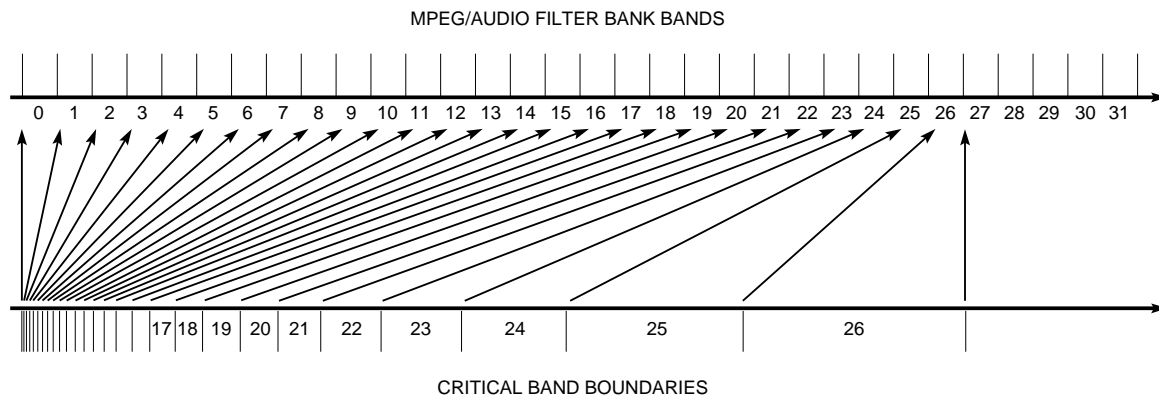


Figure 7 MPEG/Audio Filter Bandwidths versus Critical Bandwidths

The filter bank provides 32 frequency samples, one sample per band, for every 32 input audio samples. The Layer I algorithm groups together 12 samples from each of the 32 bands. Each group of 12 samples receives a bit allocation and, if the bit allocation is not zero, a scale factor. Coding for stereo redundancy compression is slightly different and is discussed later in this paper. The bit allocation determines the number of bits used to represent each sample. The scale factor is a multiplier that sizes the samples to maximize the resolution of the quantizer. The Layer I encoder formats the 32 groups of 12 samples (i.e., 384 samples) into a frame. Besides the audio data, each frame contains a header, an optional cyclic redundancy code (CRC) check word, and possibly ancillary data.

*Layer II.* The Layer II algorithm is a simple enhancement of Layer I. It improves compression performance by coding data in larger groups. The Layer II encoder forms frames of 3 by 12 by 32 = 1,152 samples per audio channel. Whereas Layer I codes data in single groups of 12 samples for each subband, Layer II codes data in 3 groups of 12 samples for each subband. Again discounting stereo redundancy coding, there is one bit allocation and up to three scale factors for each trio of 12 samples. The encoder encodes with a unique scale factor for each group of 12 samples only if necessary to avoid audible distortion. The encoder shares scale factor values between two or all three groups in two other cases: (1) when the values of the scale factors are sufficiently close and (2) when the encoder anticipates that temporal noise masking by the ear will hide the consequent distortion. The Layer II algorithm also improves performance over Layer I by representing the bit allocation, the scale factor values, and the quantized samples with a more efficient code.

*Layer III.* The Layer III algorithm is a much more refined approach.[13,14] Although based on the same filter bank found in Layers I and II, Layer III compensates for some filter bank deficiencies by processing the filter outputs with a modified discrete cosine transform (MDCT). Figure 8 shows a block diagram of the process.

The MDCTs further subdivide the filter bank outputs in frequency to provide better spectral resolution. Because of the inevitable trade-off between time and frequency resolution, Layer III specifies two different MDCT block lengths: a long block of 36 samples or a short block of 12. The short block length improves the time resolution to cope with transients. Note that the short block length is one-third that of a long block; when used, three short blocks replace a single long block. The switch between long and short blocks is not instantaneous. A long block with a specialized long-to-short or short-to-long data window provides the transition mechanism from a long to a short block. Layer III has three blocking modes: two modes where the outputs of the 32 filter banks can all pass through MDCTs with the same block length and a mixed block mode where the 2 lower-frequency bands use long blocks and the 30 upper bands use short blocks.

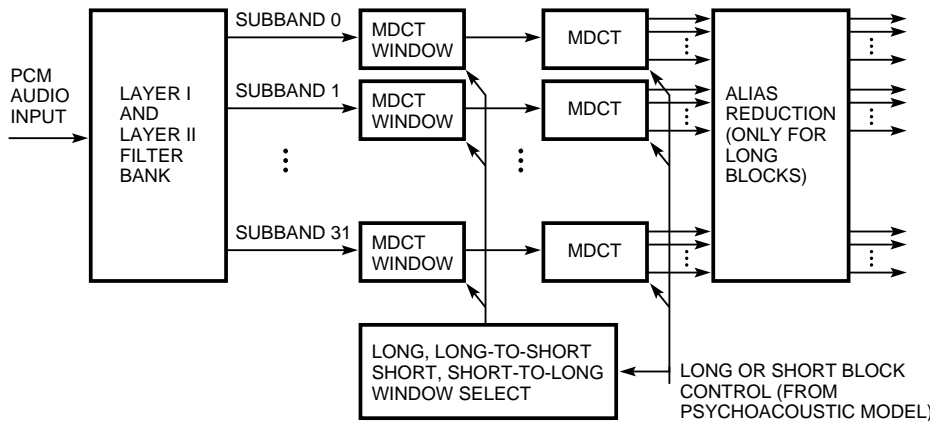


Figure 8 MPEG/Audio Layer III Filter Bank Processing, Encoder Side

Other major enhancements over the Layer I and Layer II algorithms include:

- **Alias reduction** — Layer III specifies a method of processing the MDCT values to remove some redundancy caused by the overlapping bands of the Layer I and Layer II filter bank.
- **Nonuniform quantization** — The Layer III quantizer raises its input to the  $3/4$  power before quantization to provide a more consistent signal-to-noise ratio over the range of quantizer values. The requantizer in the MPEG/audio decoder re-linearizes the values by raising its output to the  $4/3$  power.
- **Entropy coding of data values** — Layer III uses Huffman codes to encode the quantized samples for better data compression.[15]
- **Use of a bit reservoir** — The design of the Layer III bit stream better fits the variable length nature of the compressed data. As with Layer II, Layer III processes the audio data in frames of 1,152 samples. Unlike Layer II, the coded data representing these samples does not necessarily fit into a fixed-length frame in the code bit stream. The encoder can donate bits to or borrow bits from the reservoir when appropriate.
- **Noise allocation instead of bit allocation** — The bit allocation process used by Layers I and II only approximates the amount of noise caused by quantization to a given number of bits. The Layer III encoder uses a noise allocation iteration loop. In this loop, the quantizers are varied in an orderly way, and the resulting quantization noise

is actually calculated and specifically allocated to each subband.

#### The Psychoacoustic Model

The psychoacoustic model is the key component of the MPEG encoder that enables its high performance.[16,17,18,19] The job of the psychoacoustic model is to analyze the input audio signal and determine where in the spectrum quantization noise will be masked and to what extent. The encoder uses this information to decide how best to represent the input audio signal with its limited number of code bits. The MPEG/audio standard provides two example implementations of the psychoacoustic model. Below is a general outline of the basic steps involved in the psychoacoustic calculations for either model.

- **Time align audio data** — The psychoacoustic model must account for both the delay of the audio data through the filter bank and a data offset so that the relevant data is centered within its analysis window. For example, when using psychoacoustic model two for Layer I, the delay through the filter bank is 256 samples, and the offset required to center the 384 samples of a Layer I frame in the 512-point psychoacoustic analysis window is  $(512 - 384)/2 = 64$  points. The net offset is 320 points to time align the psychoacoustic model data with the filter bank outputs.
- **Convert audio to spectral domain** — The psychoacoustic model uses a time-to-frequency mapping such as a 512- or 1,024-point Fourier trans-

form. A standard Hann weighting, applied to audio data before Fourier transformation, conditions the data to reduce the edge effects of the transform window. The model uses this separate and independent mapping instead of the filter bank outputs because it needs finer frequency resolution to calculate the masking thresholds.

- Partition spectral values into critical bands — To simplify the psychoacoustic calculations, the model groups the frequency values into perceptual quanta.
- Incorporate threshold in quiet — The model includes an empirically determined absolute masking threshold. This threshold is the lower bound for noise masking and is determined in the absence of masking signals.
- Separate into tonal and nontonal components — The model must identify and separate the tonal and noiselike components of the audio signal because the noise-masking characteristics of the two types of signal are different.
- Apply spreading function — The model determines the noise-masking thresholds by applying an empirically determined masking or spreading function to the signal components.
- Find the minimum masking threshold for each subband — The psychoacoustic model calculates the masking thresholds with a higher-frequency resolution than provided by the filter banks. Where the filter band is wide relative to the critical band (at the lower end of the spectrum), the model selects the minimum of the masking thresholds covered by the filter band. Where the filter band is narrow relative to the critical band, the model uses the average of the masking thresholds covered by the filter band.
- Calculate signal-to-mask ratio — The psychoacoustic model takes the minimum masking threshold and computes the signal-to-mask ratio; it then passes this value to the bit (or noise) allocation section of the encoder.

#### *Stereo Redundancy Coding*

The MPEG/audio compression algorithm supports two types of stereo redundancy coding: intensity stereo coding and middle/side (MS) stereo coding. Both forms of redundancy coding exploit another perceptual weakness of the ear. Psychoacoustic results show that, within the critical bands covering frequencies above approximately 2 kHz, the ear bases its perception of stereo imaging more on the temporal envelope of the audio signal than its temporal fine structure. All layers support intensity stereo coding. Layer III also supports MS stereo coding.

In intensity stereo mode, the encoder codes some upper-frequency filter bank outputs with a single summed signal rather than send independent codes for left and right channels for each of the 32 filter bank outputs. The intensity stereo decoder reconstructs the left and right channels based only on independent left- and right-channel scale factors. With intensity stereo coding, the spectral shape of the left and right channels is the same within each intensity-coded filter bank signal, but the magnitude is different.

The MS stereo mode encodes the signals for left and right channels in certain frequency ranges as middle (sum of left and right) and side (difference of left and right) channels. In this mode, the encoder uses specially tuned techniques to further compress side-channel signal.

#### **Real-time Software Implementations**

The software-only implementations of the  $\mu$ -law and ADPCM algorithms can easily run in real time. A single table lookup can do  $\mu$ -law compression or decompression. A software-only implementation of the IMA ADPCM algorithm can process stereo, 44.1-kHz-sampled audio in real time on a 20-MHz 386-class computer. The challenge lies in developing a real-time software implementation of the MPEG/audio algorithm. The MPEG standards document does not offer many clues in this respect. There are much more efficient ways to compute the calculations required by the encoding and decoding processes than the procedures outlined by the standard. As an example, the following section details how the number of multiplies and additions used in a certain calculation can be reduced by a factor of 12.

Figure 9 shows a flow chart for the analysis sub-band filter used by the MPEG/audio encoder. Most of the computational load is due to the second-from-last block. This block contains the following matrix multiply:

$$S(i) = \sum_{k=0}^{63} Y(k) \times \cos \left[ \frac{(2 \times i + 1) \times (k - 16) \times \pi}{64} \right]$$

for  $i = 0 \dots 31$ .

Using the above equation, each of the 31 values of  $S(i)$  requires 63 adds and 64 multiplies. To optimize this calculation, note that the  $M(i,k)$  coefficients are similar to the coefficients used by a 32-point, un-normalized inverse discrete cosine transform (DCT) given by

$$f(i) = \sum_{k=0}^{31} F(k) \times \cos \left[ \frac{(2 \times i + 1) \times k \times \pi}{64} \right]$$

for  $i = 0 \dots 31$ .

Indeed,  $S(i)$  is identical to  $f(i)$  if  $F(k)$  is computed as follows

$$\begin{aligned} F(k) &= Y(16) \text{ for } k = 0; \\ &= Y(k + 16) + Y(16 - k) \text{ for } k = 1 \dots 16; \\ &= Y(k + 16) + Y(80 - k) \text{ for } k = 17 \dots 31. \end{aligned}$$

Thus with the almost negligible overhead of computing the  $F(k)$  values, a twofold reduction in multiplies and additions comes from halving the range that  $k$  varies. Another reduction in multiplies and additions of more than sixfold comes from using one of many possible fast algorithms for the computation of the inverse DCT.[20,21,22] There is a similar optimization applicable to the 64 by 32 matrix multiply found within the decoder's subband filter bank.

Many other optimizations are possible for both MPEG/audio encoder and decoder. Such optimizations enable a software-only version of the MPEG/audio Layer I or Layer II decoder (written in the C programming language) to obtain real-time performance for the decoding of high-fidelity monophonic audio data on a DECstation 5000 Model 200. This workstation uses a 25-MHz R3000 MIPS CPU and has 128 kilobytes of external instruction and data cache. With this optimized software, the MPEG/audio Layer II algorithm requires an average of 13.7 seconds of CPU time (12.8 seconds of user time and 0.9 seconds of system time) to decode 7.47 seconds of a *stereo* audio signal sampled at 48 kHz with 16 bits per sample.

Although real-time MPEG/audio decoding of stereo audio is not possible on the DECstation 5000, such decoding is possible on Digital's workstations equipped with the 150-MHz DECchip 21064 CPU (Alpha AXP architecture) and 512 kilobytes of external instruction and data cache. Indeed, when this same code (i.e., without CPU-specific optimization) is compiled and run on a DEC 3000 AXP Model 500 workstation, the MPEG/audio Layer II algorithm requires an average of 4.2 seconds (3.9 seconds of user time and 0.3 seconds of system time) to decode the same 7.47-second audio sequence.

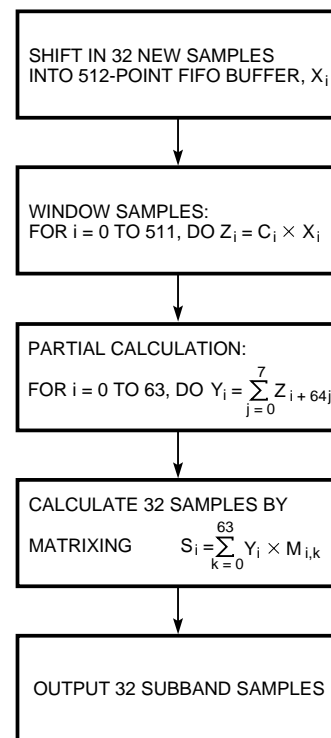


Figure 9 Flow Diagram of the MPEG/Audio Encoder Filter Bank

## Summary

Techniques to compress general digital audio signals include  $\mu$ -law and adaptive differential pulse code modulation. These simple approaches apply low-complexity, low-compression, and medium audio quality algorithms to audio signals. A third technique, the MPEG/audio compression algorithm, is an ISO standard for high-fidelity audio compression. The MPEG/audio standard has three layers of successive complexity for improved compression performance.

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