AN OVERVIEW OF VIDEO CODING TECHNIQUES

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Abstract
An update review of the advances in data compression of video signals is presented with the focus being on schemes best suited for telemetry applications. Several important features for image compression are addressed which serve as guidelines in the design of data compression schemes for custom specific applications. In accordance with this list of distinguishing attributes, a classification of existing compression algorithms is attempted. Two major classes of encoding techniques, transform and predictive encoding, are treated in thorough detail.

1 Introduction

Digital video has become an indispensable feature of the modern telemetry system. Monochrome and color TV signals are routinely transmitted in many of the government test ranges. The full bandwidth of the TV signal encoded by conventional PCM runs in the range of 60Mbps to 80Mbps while the telemetry channel rate varies depending upon the application. It is normally around 20Mbps for ground-to-ground communications and from 1Mbps to 10Mbps for air-to-ground transmission. Obviously, some kind of video compression scheme has to be employed in order to be able to achieve the required transmission rate.

A plethora of data compression algorithms has been developed during the last thirty years. This is partly due to the fact that the design of a compression scheme is generally quite application dependent; as novel applications arise, so does the demand for developing new algorithms. Some important factors that one should take into consideration in the design of a custom specific compression scheme are: image quality vs. compression ratio, implementation complexity (algorithmic complexity, run time, amenability to parallel processing, buffering requirements), robustness of statistical coding, susceptibility to channel errors, constant bit rate vs. constant image quality, progressive transmission capability, encoder/decoder asymmetry, flexibility in fine tuning to a specific application, overall system compatibility as well as the artifacts introduced to the original image as a result of the compression/decompression process. The importance of these factors varies depending upon the specific application. For example, data compression algorithms used in transmission systems are greatly constrained by real time and on-line considerations which limit severely the size and complexity of hardware. Other important issues in the design of such systems are the requirement for a constant bit rate, the robustness of an algorithm to the effects of channel errors and, finally, the requirement that the encoder and the decoder be of comparable complexity. On the other hand, for storage systems, compressor requirements are less stringent since much of the processing can be done off line. However, the decompression should be fast in order to reduce turn around or response time.

A classification of existing data compression schemes is given in table 1. The distinguishing attributes upon which this classification is made are: **a**) *dimensionality*: algorithms are classified as one dimensional schemes (for processing of data files, digitized speech, etc.) and multidimensional ones (e.g., for processing of still images or video). **b**) *lossless* vs. *lossy* algorithms. The former are able to reconstruct the original data exactly, whereas the latter introduce some distortion as a trade-off for improved compression ratio. **c**) *statistical* schemes, which require some a priori knowledge about the data source (i.e., training), vs. *adaptive* (learning) schemes, which start with no a priori information about the data source and attempt to get an estimate of the source statistics on the "fly" as they process the data. **d**) *fixed* vs. *adaptive* coding, in the sense that the parameters used are fixed or change as a function of the nonstationary data statistics.

For the rest of this paper we focus our attention on the study of video compression techniques and more specifically those ones which show some promise for use in the stringent environment of telemetry system's where bandwidth, power, size and cost, effectivenes are of prime importance.

2 Picture/Video Compression Techniques

General image compression algorithms can be classified into four main categories: Pulse Code Modulation (PCM), Predictive coding, Transform coding and Interpolative/ extrapolative coding. Besides theses four classes there are other schemes that may not fall into any of these classes but they have been developed to meet the requirements of a specific application.

2.1 Pulse Coding Modulation (PCM)

PCM is a discrete space, discrete amplitude representation of imagery information. PCM has been used as a video digitizing scheme for the purposes of storage and transmission and also for digitizing prior to the application of other more sophisticated compression algorithms.

The design of the quantizer for the PCM coding of monochrome signals can be based upon psychovisual criteria (e.g., Weber's law, which implies that the visibility of a given amount of quantization noise decreases with the luminance level, and therefore coarseness of the PCM quantizer can be increased with the luminance level). However, practical considerations generally dictate the rise of a uniform PCM quantizer on a gamma corrected monochrome camera signal. Under most viewing conditions, 7 or 8 bpp give a good video quality. For monochrome TV with a sampling rate of 8 MHz, this amounts for a bit rate of 56 to 64 Mbits/sec, a prohibitive data rate for most practical applications. Quantization with less than 5 bpp introduces contouring artifacts. Quantization noise which can be visible due to the coarseness of quantization can be reduced in many ways, e.g., by pre- and post- lowpass filtering or by a technique called *dithering*, which consists of adding pseudo-random noise to the picture before quantization, and later at the receiver subtracting the same noise from the quantized picture.

Perceptual considerations become more important in quantization of color signals [18]. Color images can be quantized as three independent component colors or as a composite color signal. Most practical color coding systems encode *color components* as opposed to the composite color signal. The simplest components to use in the PCM coding of component colors are the R,G,B tristimulus values of the pels that are usually available by a color camera. It is not necessary to quantize each of them with the same accuracy, since quantization noise is not equally visible in each of these components. Experimental results show that fewer bits can be used in the quantization of the red and blue components compared to the green signal. However, much more bandwidth efficiency can be achieved by quantizing other color components such as the Y,I,Q components that make tip the NTSC color signal or the Y,R,-Y,B-Y components that both European color TV standards, known as PAL and SECAM, employ. The total bits required for the PCM encoding of the chrominance signals is substantially smaller than the bits required for coding of the luminance (Y) component. In general, chrominance bits take up about 10-20% of the luminance bits. Sampling and quantization of the *composite color* signal requires special considerations due to the existence of the color subcarrier f_c (f_c = 3.58MHz). At first, in order to avoid aliasing and to minimize quantization noise patterns, sampling should be at a harmonic of the line frequency for NTSC, and an odd harmonic of half the line frequency for PAL. Two sampling frequencies are commonly utilized: $3f_c$, and $4f_c$. Sampling at $4F_c$ allows considerable simplifications of further processing such as filtering and coding. As for the number of quantization levels, it is generally agreed that 9bpp are required for the PCM encoding of the composite signal.

A simple design has been proposed for the digital coding of the NTSC color TV signal for telemetry applications [25]. It transforms the Y,I,Q components into Y,R-Y,B-Y components, PCM encodes them and transmits the R-Y,B-Y components on a line alternating basis resulting in an allocation of 33% of the transmission capacity to chroma information.

2.2 Predictive Coding

Often, the available imagery data has statistical dependency or redundancy from one sample to the next. In such cases predictive coding schemes are employed. The principal components of a typical predictive system are its predictor and quantizer. An important aspect of this scheme is that prediction is based on the output rather than the input samples from the past. This results in the predictor being in the feedback loop around the quantizer so that the quantizer noise at a given step is fed back to the quantizer at the next step (fig.1). This has a stabilizing effect that prevents accumulation of errors in the reconstructed signal. The main advantage of a predictive system over a PCM system is the exploitation of statistical redundancy so that only uncorrelated data with a reduced variance are presented to the quantizer. Thus, the expected effectiveness of a predictive system is directly related to the covariance of the data. Depending upon the number (L) of levels of the quantizer, a distinction is often made between Delta Modulation (DM), for which $L = 2$, and Differential Pulse Code Modulation (DPCM), with L greater than 2. The DM has not found great use in image compression, due basically to the high sampling rates that it requires. On the other hand, DPCM is currently the most widely used video coder, mainly, due to its simplicity and ease of implementation. This technique allows compression ratios around 2.5:1. Adaptive DPCM (ADPCM) schemes achieve compression ratios around 4:1.

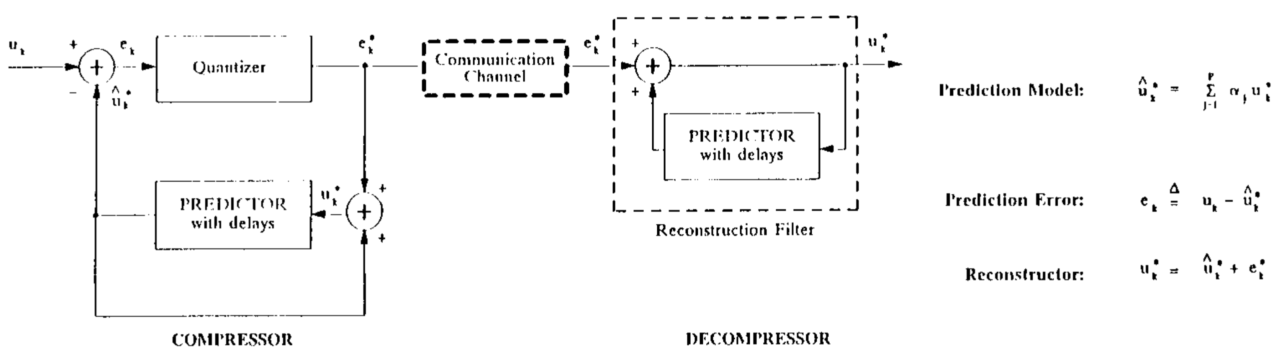

Figure 1: DPCM system.

In DPCM coding the signal is first sampled at or around its Nyquist rate. The differential signal which is quantized and coded for transmission comes from the difference between the actual pixel to be encoded and a prediction of its value. In its simplest form, DPCM uses the coded value of the horizontally previous pel as a prediction (*one-dimensional intrafield coding*). More sophisticated predictors achieve better performance by using more pels in the present field as well as previous fields and frames. These two- and three-dimensional predictors are called *intrafield*, *interfield* and *interframe* predictors, respectively. The two-dimensional prediction reduces the error on vertical edges, but increases the error on horizontal edges as compared to one-dimensional ones. However, the overall peak prediction error is reduced considerably with two-dimensional predictors. Various types of linear predictors have been used, such as, autoregressive (AR), moving average (MA) or Kalman filter ones [13]. It has been shown [28] that a moving average (MA) predictor is more suitable for Synthetic Aperture Radar (SAR) data compression than the more widely used AR predictor. Furthermore, predictors can be either fixed or adaptive. In the latter case, the prediction is switched from a set of predictors, with the decision of switching based upon some calculation from previously encoded pels. In the case of intraframe coding, such calculations are: a) a measure of directional correlation, which is being used for the selection of a predictor along the direction of maximum correlation (e.g., Graham's predictor) and b) the absolute prediction error for each predictor under consideration, the one with the least absolute error is chosen in order to encode the current pel. The performance of a predictor depends heavily on the busyness of the image. For scenes with low details and small motion, interframe prediction achieves the best compression. In scenes with higher detail and motion, interfield coding has an advantage. As the motion in the scene is increased further, intrafield coding does the best. The RCC-209-88 test range standard for transmission of monochrome digital video signals employs a one-dimensional DPCM coding scheme, so that no degradation of vertical resolution occurs. Also it does not allow for any interframe coding, since this would blur of objects in motion [23]. The performance of interframe coders improves considerably, in terms of both the achieved compression ratio and image quality, when the speed and direction of moving objects is taken into account. In *motion compensated interframe coding* schemes, the direction of motion of the object is tracked either by a block matching technique or by a pel recursive technique [22]. Pel recursive techniques are preferable in scenes with multiple moving objects. A DPCM codec with a variable stage motion search using block matching was recently applied to a test frame sequence provided by NASA with very good results [17] (1.35 bpp average bit rate was reported). Special consideration has to be taken in the design of predictors for color signals. In the case of component color coding, an adaptive predictor is usually designed to match the characteristics of the luminance component alone and then the same predictor is used for encoding of chroma, components. Design of predictors for the composite NTSC signal poses extra difficulties, since most of the correlation in the adjacent pels is lost due to the presence of modulated chrominance components. Nevertheless, a few codecs of this type have been designed [24].

The differential signal is quantized with a fixed or adaptive quantizer. Three types of degradations may be seen as a result of DPCM quantization. These are referred to as granular noise, slope overload and edge busyness. It has been realized for some time that, for subjective reasons, quantizers should not be designed based on the Mean Square Error (MSE) criterion but, rather, on psychovisual criteria. Adapting the DPCM quantizer by adjusting the number of quantization levels according to the local activity in the image results in considerable reduction of the bit rate. Clearly, the quantizer output bit, rate for a DPCM codec must exceed 1 bpp. Experimental results have shown that the distribution of' the quantizer levels for most images is highly nonuniform and, therefore, further lossless compression can be achieved by using variable-wordlength codewords. The Huffman code (sometimes referred to as entropy coding), the Lempel-Ziv [27] and the arithmetic code [5] are one dimensional lossless compression schemes that have been utilized for the compression of the DPCM codewords. The resulting concatenated coding algorithms are often called Variable Length DPCM (VLDPCM). For most pictures the average bit rate using a lossless coding scheme is about 1 bpp less than the corresponding bit rate for a fixed length code. However, one disadvantage of variable-length coding is that it normally requires a rate buffer for channel rate equalization. This, in turn, increases the complexity of the system.

One important aspect in the design of predictive codecs is the effect of transmission bit errors to the reconstructed image. Due to the differential feature of DPCM coding, a single bit error in any pel introduced by the channel noise usually propagates and could possibly affect all subsequent pels. The situation gets worse with VLDPCM, where a misinterpretation of a single bit may result in desynchronization of the entire bit stream since the codeword's length is not fixed. Several methods for enhancing VLDPCM images corrupted by transmission errors have been proposed [14]. One commonly used technique is hybrid PCM/DPCM, where predictor coefficients are periodically set to zero and during the resetting a PCM value is transmitted. Most techniques, though, fail when transmission takes place over very noisy channels in which case the only resource may be the use of powerful forward error correcting codes (e.g., Recd-Solomon or convolutional codes).

VLDPCM codecs for telemetry applications have been implemented in hardware and are available today [11,9].

2.3 Transform Coding

In transform coding compression is achieved by an energy preserving transformation of the given image pels into another set such that the maximum information is packed into a minimum number of samples [12]. Most commonly used transforms are linear transformations. The Karhuncn-Loéve (KLT) is the best linear transformation in the sense that it leads to uncorrelated coefficients. But, it is rarely used in practice because of its computational load. On the other hand, the Discrete Cosine transform (DCT), which is a suboptimal algorithm, has been proved to be the best linear transformation for practical applications. DCT is preferred over the KLT, since the DCT is signal independent, it is a good approximation to the KLT for a large class of signals with low-pass spectra, and can be computed by means of fast algorithms. Other transforms that can be computed by means of fast algorithms are: Discrete Fourier (DFT), Hadamard-Walsh (WHT), Haar, Slant and Discrete Sine transform (DST).

Several parameters can be optimized in the design of a transform codec. The specific shape and size of the transform processing block affect directly the performance and quality of the compression scheme. Extensive simulation results have shown that for a large class of images square blocks of size 16x16 pixels yield the best performance. The optimization of the quantization levels can be based on the mean square error criterion as well as preceptual criteria. Transform coding may also be adaptive by adjusting the parameters of the coder to match local variations for nonstationary images. In connection with hybrid codecs, motion-adaptive techniques have been investigated, particularly, for reducing the blurring of moving objects.

In coding of color signals approaches similar to those for DPCM coding have been taken. In general, component coding achieves better performance, whereas coding of the composite signal sometimes yields simpler implementations since it avoids computing the signal components. Notice, though, that not all linear transforms are appropriate for compressing composite color signals. Such a transform should contain among its basis vectors both sine and cosine functions in order to be able to match the phase and amplitude of the color subcarrier f_c. These vectors are present in the KLT and DFT transforms but not in the DCT.

A drawback in transform coding is the introduction of artifacts known as “blocking-effect” when operating at very low bit rates. Methods for the reduction of blocking effects have been recently suggested [20]. Recursive Block Coding (RBC) is an important new technique which extends the KLT concept and, at the same time, substantially reduces the blocking effect [8].

In general, transform coding is conceived as being superior among the various compression techniques. However, it suffers from a major drawback i.e., its computational complexity for real time implementations. With the evolution, though, of VLSI technology and its widespread use, the hardware complexity of transform coders may not remain a disadvantage for very long. For example, a concurrent VLSI architecture for the implementation of a 16x16 DCT operating at a 14.3 MHz sample rate it is known to exist [26].

2.4 Hybrid Transform Coding

Hybrid transform coding combines the advantages of simple hardware complexity of DPCM coders and the high performance of transform coders, particularly at low bit rates (e.g., less than 1 bpp). Both intraframe and interframe hybrid techniques have been developed. Intraframe hybrid transform coding is typically implemented by first transform coding in one spatial dimension and then predictive (DPCM) coding of the transform coefficients in the other dimension [3]. The theoretical framework for quantization and coding of hybrid transform values is very similar to that of transform coding itself. It is easily adaptable to coding and filtering of noisy images and to changes in data statistics. It is less sensitive to errors than DPCM, but is not as robust as transform coding. Its coding performance lies between transform coding and DPCM. Experimental results of adaptive interframe hybrid transform coding are comparable to adaptive interframe transform coding, which is much more complex to implement. With interframe hybrid transform coding, motion compensation can also be used to reduce the bit-rate significantly.

Hybrid coders have been implemented for real-time data compression of images acquired by remotely piloted vehicles [21] as well as for video coding at sub-primary rates [22, ch.6.6.2]. Typical compression ratios achieved by the Hybrid transform coding are around 8:1.

2.5 Interpolative/Extrapolative Coding

Most commonly used interpolators are zero-order and first order (linear) interpolators, resulting in compression ratios around 4:1. Highcr order polynomials or cubic splines can also be used, but their complexity does not justify the improvement on the image quality. In some cases, it is possible to improve the quality of interpolation by using estimates of motion objects in the scene (e.g. motion adaptive interframe interpolator). In general, interpolative coders are useful for applications where a very low bit rate is required, and where it might not be possible to encode each sample (e.g., during buffer overflow).

2.6 Other Coding Algorithms

A number of important coding schemes do not fall in any of the previously discussed four classes of coders. Among them, four well promising schemes are: vector quantization, subband (pyramid) coding, second generation techniques and fractal transform. This section briefly discusses these techniques.

Vector Quantization (VQ) has emerged recently as a powerful technique for image and video coding [10]. The main advantage of VQ is the simple receiver structure which consists only of a look up table. VQ is a mapping of an input vector to an output reproduction vector which is chosen from a finite dictionary. The critical encoding task of VQ is to find, according to a well defined metric, the best matching codevector from the codebook for a given input vector. A lot of research has been done in developing efficient methods of creating the codebook from a set of training images. The LGB algorithm [19] is an optimum iterative procedure based upon the MSE criterion. A problem with LGB and its variants is the excessive time in building the codebook, something that should be expected since it is essentially all exhaustive search. Another method developed by Equitz is called *Nearest Neighbor* algorithm and has computational complexity that grows only linearly with the size of the training set but its storage requirements are doubled compared to LGB. *Multistage* VQ reduces both the search time and the storage requirements. However, the principal alternative to quantizers based on the LGB algorithm is the *lattice quantizer* [4]. While the effectiveness of VQ is undisputed, a major obstacle to its use is the computational complexity of real-time implementations. Nevertheless, significant improvements have been made in the design of real-time image and video coders by using dedicated VLSI processor architectures [7,6]. As VLSI technology continues to improve, the real-time implementation of VQ coders will become more attractive.

Subband coding (SBC) combines features of predictive and transform coding methods, achieving compression ratios around 10:1 [29]. The basic idea behind SBC is to split up the frequency band of the signal and then DPCM code each subband with coders carefully matched to the statistics of the subband. In addition to the good compression ratio, this scheme also lends itself nicely to progressive transmission (a desirable feature in a browsing system). SBC is related to the synthetic-high-system introduced by Schreiber et al. in 1959, as well as the recent *pyramid* coding method of Burt and Adelson [1].

The functional principle of synthetic-high-system also gave a lot of insight to develop a whole new class of algorithms, collectively known as *second-generation techniques* [16]. Recent neurophysiological results about the human visual system strongly suggest the use of contour-texture models for image processing and coding. Second generation techniques rely on this picture description model in order to achieve compression ratios as high as 70:1 on grey-level still pictures. The picture segmentation is usually based upon pattern recognition and artificial intelligence approaches.

Recently, Professors M. Barnsley and A. Sloan at the Georgia Institute of Technology developed an innovative technique called *fractal transform* for compressing and analyzing of digital pictures. A practical system implementing this transform was funded by the Defense Advanced Research Projects Agency (DARPA) and its performance was demonstrated in November, 1989. The system, operated by a trained operator, took about 100 hours to compress a 780-by-1024 pixel photoreconnaissance satellite image, but, achieved compression ratio greater than 1000 to 1. An updated fully automated implementation of the fractal transform on an AMT distributed array processor, can process a 256x256 pixel black and white image in under 10 sec. Barnsley estimates that putting the transform on a special chip would allow it to handle up to 30 pictures per second. Barnsley and Sloan are also currently looking at applying their transform to the high-definition TV (HDTV) [2,15].

3 Conclusion

In this study we discussed the fundamentals as well as some details of several basic and state of the art techniques in video compression. Emphasis was put on techniques which are either currently applied to or have the potential of future application to telemetry systems.

Predictive coding is extensively used in the telemetry systems of today, mainly because of its simple hardware implementation which is appropriate for real time applications. A lot of work, though, remains to be done in the area of adaptive predictive coding. In the meanwhile, advances in VLSI design make the hardware implementation of transform coding more appealing. Hybrid transform coding emerges as an important compromise between the superior performance of the transform coding and the simplicity of the DPCM. Telemetry systems have to benefit a lot from the research done in the area of hybrid transform for commercial applications (videoconference). The introduction of more powerful computing machines and special purpose hardware to the modern telemetry systems facilitates the employernent of more advanced data compression schemes like the second generation techniques or fractal transformation.

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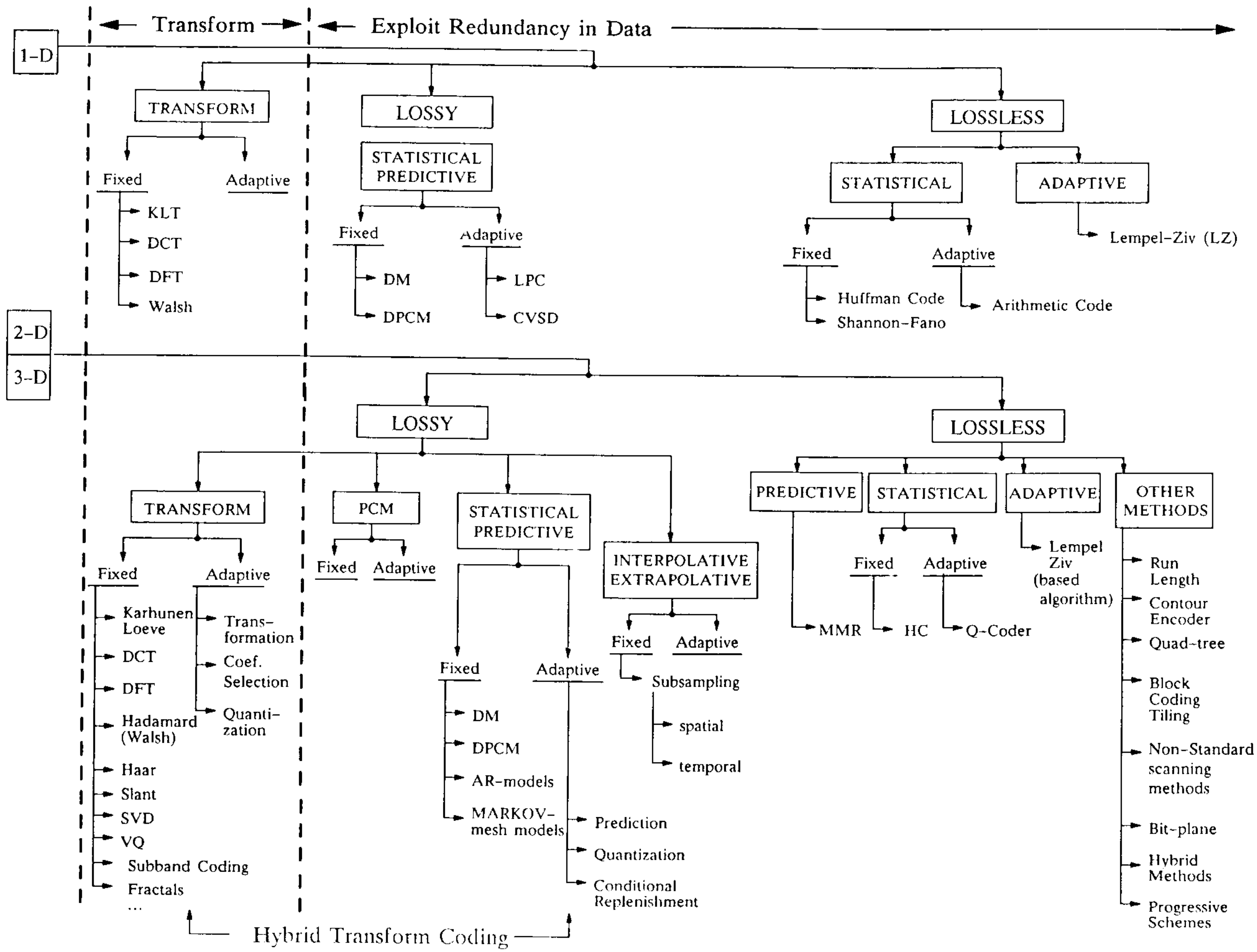

Table 1: Classification of data compression algorithms