A Tutorial on Image/Video Coding Standards

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***Abstract*—The field of image and video compression has gone through rapid growth during the past thirty years, leading to various coding standards. The main goal of continuous efforts on image/video coding standardization is to achieve low bit rate for data storage and transmission, while maintaining acceptable distortion. In this paper, various developmental stages of image and video compression standards are reviewed, including JPEG and JPEG 2000 image standards, MPEG-1, MPEG-2, MPEG-4, H.261, H.263, H.264/MPEG-4 AVC, and the latest international video standard HEVC as well as Chinese video coding standard AVS. Key features and major applications of the standards will be briefly introduced and the compression performance of the standards at each stage will be compared and discussed.**

I. Introduction

The advent of the semiconductor computer in 1960s inaugurated a new era in digital processing and communication. Digital image processing was brought to public attention by the success of the space program [1]. In the early 1980s, thanks to the development of hardware, especially the considerable progress in very large scale integration (VLSI), digital image processing became more and more popular. At the same time, several types of video production equipment were introduced in the late 1970s to the early 1980s, such as time base correctors, which took a standard analog composite video input and digitalized it internally. The digitalizing of video made it easier to be processed and accelerated the development of video broadcasting.

The modern society has made itself into the global information age in which images and videos can be found everywhere in people's daily life. Nearly 1.42 million photos are uploaded to Flickr every day in average [2] and over 2.6 million hours of video are uploaded to YouTube each month [3]. Also the resolution of image and video grows dramatically from 100x100 in the 1960s to around 5000x3000 for image and 1980x1080 for video nowadays. However, the size of raw digital source data can be so tremendous that enormous resources are required for storage and transmission. For example, the size of a 150-minute color movie with 30 frames per second and 720x480 resolution is as large as 280 GB without compression, not to mention the situation when the movie needs to be transmitted through the Internet whose bandwidth can be lower than 10 Mbit/s. In light of this, digital image and video compression technology is a necessity even though computer power, storage, and the network bandwidth have increased significantly.

Image and video data compression refers to a process in which the amount of data for representing the input signal is reduced to a certain degree in order to achieve a higher efficiency in storage and transmission. Compression can be achieved by reducing the redundancies inherent in image and video, including spatial, temporal, statistical and psychovisual redundancy [1]. In general, compression methodology is classified into two categories, lossless compression and lossy compression. Lossless compression compresses the data in such a way that the reconstructed signal is exactly the same as the original one. According to the Shannon's source coding theorem, the coding rate (average number of bits per symbol) can not be less than the Shannon entropy of the source signal, without introducing distortion to the reconstructed signal. So there is a lower bound for the lossless compression rate. However, in real cases, some distortion in the reconstructed signal can be acceptable to further lower the bit rate, where lossy compression is more appealing. For example, when it comes to natural images and video surveillance, lossy compression is preferred since the unnecessary details can be removed to save storage and transmission resources. The key issue in the lossy compression is to make the coding rate as small as possible while maintaining the same visual quality.

The field of image and video compression has experienced a rapid growth in recent years, various coding algorithms have been invented and improved. The development of international compression standards has accelerated the improvement of image and video coding applications [4]. Several still image compression standards have been finalized like JPEG [5] and JPEG 2000 [6]. Video compression standards includes MPEG-1 [7], MPEG-2 [8], MPEG-4 [9], H.261 [10], H.263 [11], H.264/MPEG-4 AVC [12], and the latest video coding standard HEVC [13]. Fig. 1 summarizes the evolution of image/video coding standards by the International Telecommunication Union (Telegraphy section) (ITU-T) and the International Standards Organization (ISO) and their joint work from 1984 [14].

The rest of this paper is organized as follows. First of all, Section II introduces two famous image lossy compression standards JPEG and JPEG 2000 while several lossy video compression standards are reviewed in Section III. Detailed simulation comparison of the image and video compression standards are shown in Section IV. Finally Section V concludes the paper.

II. Image Compression Standards

Digital images contribute significantly to areas like the Internet, digital photography, medical imaging, remote sensing,

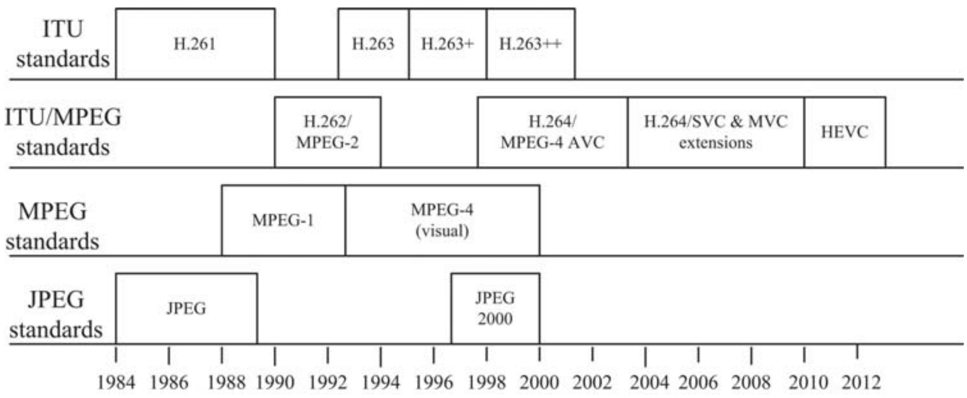

Fig. 1. History line of image/video coding standards by ITU-T and ISO/IEC committees

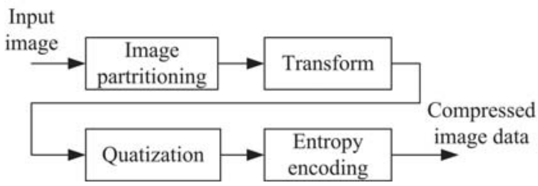

Fig. 2. General Structure of Image Coding Standards

surveillance, facsimile, *etc.* However the size of raw data can be so tremendous that it is difficult to have the data stored and transmitted. Fortunately, the development of image compression technologies provides a solution to the problem. The standardization process of image compression started from the mid-1980s, when ITU-T and ISO began to work together on establishing an international compression standard for continuous-tone still images, both grayscale and color [5], referred to as the Joint Photographic Experts Group (JPEG). At the turn of the millennium, the JPEG committee decided to figure out a new image compression standard, named JPEG 2000 standard [15], with the aim of providing greater flexibility and interchangeability than JPEG. The encoding process of image compression is shown in Fig. 2, where transform is performed to decorrelate the signal and quantization is used to reduce the amount of information required to be stored or transmitted. In the following sections, a brief introduction of the two standards will be provided.

A. JPEG

In the mid-1980s, the members of ITU-T and ISO cooperated to establish a standard for compressing grayscale and color still images [16]. This effort was known as JPEG, in which the word "joint" indicated the collaboration between ITU-T and ISO. After evaluating different coding schemes, a discrete cosine transform (DCT)-based coding algorithm was chosen as the baseline of JPEG in 1988. The JPEG group continued simulating and evaluating the algorithm, and made JPEG an international standard in 1992 [5]. The JPEG coding standard still serves as the most widely used compression algorithm today.

JPEG was proposed for effective exchange of images across application boundaries. Its application can be found in diverse storage and transmission domains, such as the Internet, digital professional and consumer photography, and video. The JPEG standard specifies two classes of encoding and decoding, called lossless and lossy compression. The lossless coding scheme is based on predictive coding method using neighboring pixel values, designed for applications that cannot tolerate any distortion [14]. On the other hand, the well-known DCT is employed for the lossy mode which serves as the base-line of JPEG and achieves sufficient compression performance for many applications. In order to compress an image using JPEG, it is firstly divided into many non-overlapping 8x8 blocks. For each 8x8 block, DCT is applied to exploit the spatial correlation followed by the quantization of the DCT coefficients based on quantization tables. At last, an appropriate entropy coding technique is selected to encode the quantized DCT coefficients to get the final bit stream. JPEG defines four distinct modes of operations: sequential DCT-based mode, progressive DCT-based mode, lossless mode and hierarchical mode [1]. For each coding mode, either Huffman coding or arithmetic coding is implemented.

B. JPEG 2000

So much has changed since the introduction of JPEG in 1980s, and the market demand lead to the birth of a new standard JPEG 2000 to provide better quality and capability for market evolution that JPEG failed to cater for. So after issuing JPEG, ISO and ITU-T continued the work on the next image compression standard JPEG 2000 [15], which was approved in 2002 as an international standard. The target market of JPEG 2000 is assumed to be remote sensing, color fax, printing, scanning, digital photography, medical imagery, digital libraries/archives, Internet, e-commerce, *etc.*

The detailed requirements for JPEG 2000 involve improving compression efficiency, lossy and lossless compression, multiple resolution representation, embedded bit-stream (progressive decoding and SNR scalability), tiling, region-of-interest (ROI) coding, error resilience, random codestream access and processing, improved performance to multiple compression/decompression cycles and a more flexible file format [6]. The key technique of JPEG 2000 is the discrete wavelet transform (DWT). The merit of wavelet transform is that it provides not only high coding efficiency but also spatial and quality scalability features. Moreover, JPEG 2000 does not suffer from the blocking artifacts since it does not involve 8x8 block based transform.

In terms of functionality, JPEG 2000 is indeed a great improvement over JPEG, providing better low bite rate compression performance, allowing larger image size, simplifying the decomposition architecture, *etc.* However there is no truly substantial improvement, especially at medium and high quality settings, although the new standard shows higher compression efficiency. Other than that, JPEG 2000 can be more complex than JPEG, so JPEG still serves as the most widely used image format given its low complexity and high lossy compression quality [17].

III. Video Compression Standards

Nowadays, digital video is used in a wide range of applications including DVD, digital TV, HDTV, video telephony, and teleconferencing. These digital video applications are based on advanced computing and communication technologies as well as efficient video compression algorithms. The standardization process of video coding continuously improves the development of video compression technology. The Video Coding Experts Group (VCEG) of the ITU-T is responsible for standardization of H.261 and H.263. Another important video coding standardization group is the Moving Picture Experts Group (MPEG) formed by ISO and IEC (International Electrotechnical Commission) to produce MPEG-1 and MPEG-4. These two groups collaborated together to produce H.262/MPEG-2 in 1994 and formed the Joint Video Team (JVT) in 2001 for the development H.264/MPEG-4 AVC. Cooperation of the two groups in 2010, the Joint Collaborative Team on Video Coding (JCT-VC), brought about a new generation video coding standard H.265 also known as High Efficiency Video Coding (HEVC). The general structure of the video codec is shown in Fig. 3. Two types of frames are introduced in video coding: Intra-frame and Inter-frame, where Intra-frame only exploits the spatial correlation to predict the signal while Inter-frame also uses the temporal correlation to further reduce the redundancies. The following sections will give a brief introduction of each standar mentioned above. Moreover, Audio Video Standard (AVS), which is developed by the China Audio Video Coding Standard Working Group, will also be briefly discussed.

A. Previous standards

Before H.264/MPEG-4 AVC and HEVC are developed, the video compression standards produced by VCEG and MPEG include H.261, MPEG-1, H.262/MPEG-2, H.263 and MPEG-4. H.261, the very first one of the H.26x standards in the domain of VCEG, started the practical digital video coding standardization. The coding scheme follows the so-called block-based hybrid video coding approach. The concept of macroblock (MB) which serves as the basic processing unit first appeared in H.261 [10]. The inter-picture prediction reduces temporal redundancy with integer-valued motion vectors. Though significant improvements in compression capability have been made, H.261 still serves as a milestone in the field of video coding.

In 1992, MPEG-1 was designed by MPEG for CD-ROM application [7]. MPEG-1 is based on motion compensated transform coding, in which main coding tools are color conversion to YUV and down sampling in UV domain, spatial de-correlation with 8x8 DCT , and spatial redundancy de-correlation with bi-directional inter prediction. MPEG-1 used to be prevalently used by many digital satellite/cable TV services before being replaced by H.262/MPEG-2 which was designed by MPEG and VCEG jointly to meet the need of entertainment TV for transmission media like satellite and CATV, and digital storage media such as DVD [8]. To efficiently compress interlaced digital video at broadcast quality, many new features were developed. Frame picture and Field picture were defined, and accordingly frame/field motion compensation with blocks of size 16x8 pels was introduced. The scalability tools as functionality tools were first defined. MPEG-2 provides compression support for TV quality broadcasting of digital video, and also supports the format of movies and other videos on DVD and similar discs.

In 1995, the VCEG developed H.263 for video conferencing at a low bit rate in the mobile wireless communication scenario [11]. Till now, H.263 still plays a dominant role in video conferencing and cell phone codec. The basic configuration is based on H.261 which adopts a hybrid of inter-picture prediction utilizing 16x16/8x8 motion compensation with half-pel resolution and transform coding with 8x8 block DCT [18]. H.263 is superior to previous video coding standards at different bit rates. Started in 1998, MPEG-4 was derived to deal with multimedia content in object-based, interactive, and non-linear way [9]. MPEG-4 covers novel profiles and levels with many novel coding tools such as interactive graphics, object and shape coding, wavelet-based still image coding, face modeling, scalable video coding and 3D graphics. MPEG-4 provides the following functions: improved coding efficiency over MPEG-2, ability to encode mixed media data (video, audio, speech), error resilience to enable robust transmission and ability to interact with the audio-visual scene generated at the receiver.

The above mentioned video coding standards are widely used, however their usage requires the manufacturers to pay a huge amount of fees to companies holding the patents. In order to reduce the foreign dependence on the key intellectual properties, the Audio Video Standard (AVS) was founded by the China Audio Video Coding Standard Working Group in June 2002 . AVS1 is the first generation of AVS which was finalized in September 2008 [19] and can provide the coding efficiency two times higher than MPEG-2, while the complexity is only 30%, and 70% compared to H.264/MPEG-

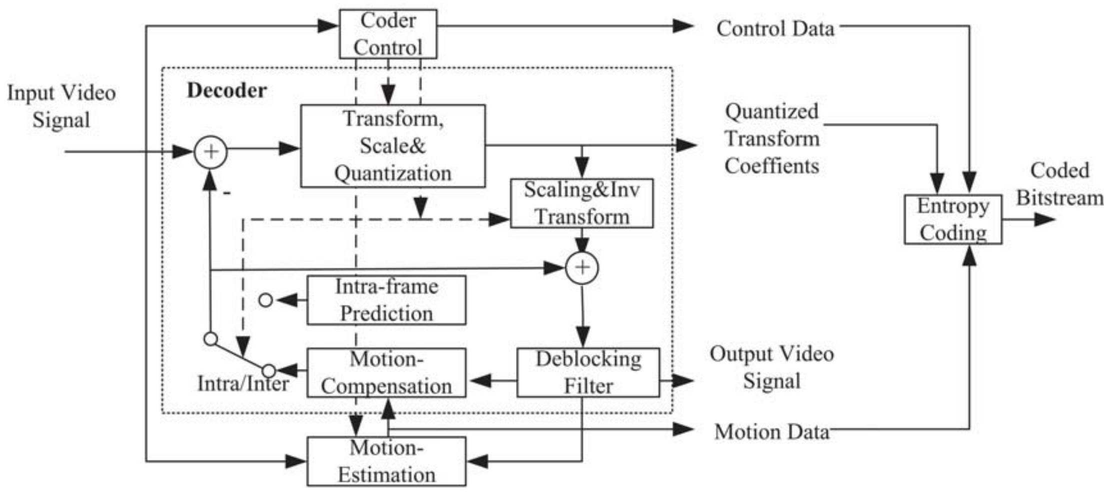

Fig. 3. General Structure of Video Coding Standards

4 AVC [20]. The second generation of AVS video coding standard (AVS2) will be finalized in Dec 2013. AVS2 is expected to improve coding efficiency by two times compared to AVS1, under high definition or higher resolution conditions [21].

B. H.264/MPEG-4 AVC

In 2003, the first version of H.264/MPEG-4 Part 10 or AVC (Advanced Video Coding) was finalized which is currently one of the most popular coding standards for the recording, compression, and distribution of high definition video. It was developed by the ITU-T VCEG together with the ISO/IEC MPEG, and the joint group was known as JVT [12]. The standard aims to compress video to half the rate of previous video standards (MPEG-2, H.263 and MPEG-4) while retaining good quality [22].

H.264/MPEG-4 AVC contains a number of new features to compress video much more effectively and to provide more flexibility for application in various network environments. In particular, the features include: variable block-size motion compensation with block sizes as large as 16x16 and as small as 4x4, enabling precise segmentation of moving regions, quarter-pixel precision for motion compensation, enabling precise description of the displacements of moving areas, an in-loop deblocking filter that helps prevent the blocking artifacts, context-adaptive binary arithmetic coding (CABAC), context-adaptive variable-length coding (CAVLC) [23].

One of the major features added to the standard is Scalable Video Coding (SVC). It allows the encoding of high quality bitstreams that contain sub-bitstreams. By dropping packets from the high resolution video, a subset video bitstream is derived and reduces the bandwidth needed, leading to a lower resolution temporally and spatially. Another major feature is Multiview Video Coding (MVC). It enables the encoding of the bitstream that represents more than one view of a video scene, for instance, stereoscopic 3D video coding.

H.264 performs radically better than MPEG-2 video with the same quality at half of the bit rate or less, especially in high bit rate and high resolution situations. So it becomes the leading standard and has been adopted in many video coding applications such as the iPod and the Playstation Portable, as well as in TV broadcasting standards such as DVB-H and DMB. Moreover, H.264 is best known as being one of the codec standards for Blu-ray Discs. Table I summarizes the applications of each video coding standards in our daily life.

C. HEVC

In early 2013, the first version of the standard High Efficiency Video Coding (HEVC) was published as the successor to H.264/MPEG-4 AVC. HEVC is derived to provide sufficiently higher compression capability to fulfill the need of continuous demand of higher quality video transmission and also focuses on the increasing need for parallel proccsesing. HEVC encoder is still based on the hybrid predictive transform coding approach, with motion-compensated prediction, intra-picture prediction, in-loop filtering, 2D transformation, and adaptive entropy coding [24]. Compared to previous video compression standards, larger coding unit structure size with more complex sub-partitioning is introduced in HEVC. The coding unit (CU) structure replaces the macroblock structure and each CU contains one or several variable-block-sized prediction unit(s) (PUs) and transform unit(s) (TUs). Advanced motion vector prediction (AMVP) is employed to include most probable candidates from neighboring PUs and the reference picture. Quarter-sample precision MVs are used with 7-tap or 8-tap filters for interpolation of fractional positions. An in-loop deblocking filter friendly to parallel processing is utilized. Sample adaptive offset (SAO) is also used within the interpicture prediction loop to better reconstruct the original signal amplitude. HEVC doubles the data compression ratio compared to H.264/MPEG-4 AVC at the same level of video quality [25], meanwhile, supports 8K UHD and resolution up to 8192x4320. Considering range scalable coding and 3D

TABLE I
MAJOR APPLICATIONS OF VIDEO COMPRESSION.

Applications	Bit Rate	Video Standards
Digital Television Broadcasting	2 ... 6 Mbps (10 ... 20 Mbps for HD)	MPEG-2, H.264/AVC
DVD video	6 ... 8 Mbps	MPEG-2, H.264/AVC
Internet video streaming	20 ... 200 kbps	H.263, MPEG-4 or H.264/AVC
Videoconferencing, videotelephony	20 ... 320 kbps	H.261, H.263,H.264/AVC
Video over 3G wireless	20 ... 200 kbps	H.263, MPEG-4

TABLE II
TEST IMAGES.

Name	Resolution
Cameraman	256x256
Mandrill	512x512
Lena	512x512
Peppers	512x512

video extensions, the standard still remains under continuous development.

IV. EXPERIMENTAL SIMULATIONS

In this section, the coding performance of several image and video coding standards are simulated and compared. First of all, the image coding standards JPEG and JPEG2000 are tested under different compression rate in Section IV-A and several video coding standards of H.26x and MPEG series together with H.264 and HEVC are tested under different bit-rate regions in Section IV-B. Details are discussed as follows:

A. Image Compression Standards

In order to compare the compression performance of JPEG and JPEG 2000 coding standards, several test images are selected as listed in Table II with different resolutions. Test images are the natural images with different properties.

For each test image, we compress it using JPEG and JPEG 2000 under different quality respectively. PSNR and compression rate (bits per pixel) are measured as the comparison metric. The rate-distortion (RD) curves for test images are plotted in Fig. 4, several subjective test evaluation is illustrated in Fig. 5, with PSNR and compression rate for each image displayed.

Fig. 4 clearly shows that JPEG 2000 is superior to JPEG in term of PSNR under different compression rate. Also the subjective evaluation in Fig. 5 suggests that JPEG 2000 performs much better than JPEG especially when the bit rate is low. The two images in the same row are with similar compression rates, but the one at the bottom for JPEG 2000 has much less artifact than the one on the top for JPEG. The blocking artifacts are greatly reduced due to the use of DWT technique in JPEG 2000. Nevertheless, JPEG is still the most widely used image format given its low complexity and high lossy compression quality.

B. Video Compression Standards

In this section, the video coding standards are simulated and compared. Several test sequences are selected as listed in Table

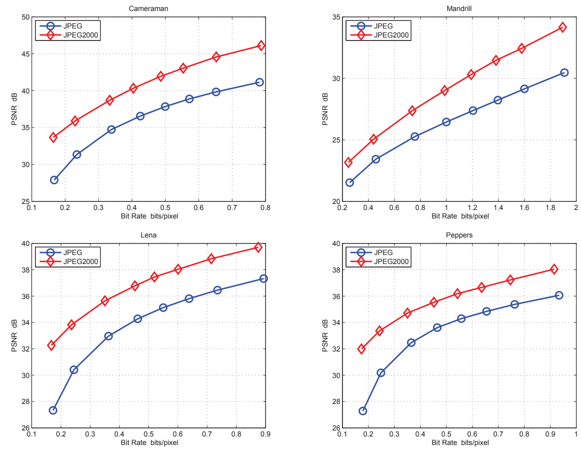

Fig. 4. RD curves for test images: From left to right, top to bottom: Cameraman, Mandrill, Lena, Peppers.

TABLE III
TEST SEQUENCES.

Name	Resolution	Frames to be Encoded
Foreman	176x144	300
Football	352x288	300
RaceHorses	832x480	300
Johny	1280x720	600

III, which indicates different resolution and frame number for each of the four video sequences. In addition, for Foreman and Johnnythe, the backgrounds are almost static, while those for Football and RaceHorses involve fast and irregular motions.

Each sequence is compressed by various video coding standards, such as H.26x series, MPEG series, H.264/MPEG-4 AVC and HEVC. Different QPs are used to evaluate the coding performance at all kinds of bit rate regions. All Intra (AI), lowdelay (LD) conditions are used for the testing. Moreover, for AI condition, since all the frame are encoded independently, we also test the situation when all the frames are encoded using JPEG and JPEG 2000. Since H.261 and H.263 only support limited choice of resolution, only Foreman and Football can be tested using H.261 and H.263 while RaceHorses and Johnny cannot. FFMPEG [26] is used to encode the sequences by MPEG-1, MPEG-2 MPEG-4, H.261 and H.263. JM software version 18.5 is used as the H.264 codec and HM 11.0 is used as the HEVC codec version.

The rate-distortion (RD) curves of the test sequences are plotted in Fig. 6 for AI condition and Fig. 7 for LD condition.

(a) PSNR: 27.88 dB, Rate: 0.167

(b) PSNR: 34.74 dB, Rate: 0.339

(c) PSNR: 37.84 dB, Rate: 0.500

(d) PSNR: 39.83 dB, Rate: 0.652

(e) PSNR: 33.66 dB, Rate: 0.164

(f) PSNR: 38.69 dB, Rate: 0.333

(g) PSNR: 41.94 dB, Rate: 0.486

(h) PSNR: 44.57 dB, Rate: 0.652

Fig. 5. Subjective test evaluation for JPEG and JPEG 2000 under similar compression rate: Top row JPEG, bottom row JPEG 2000.

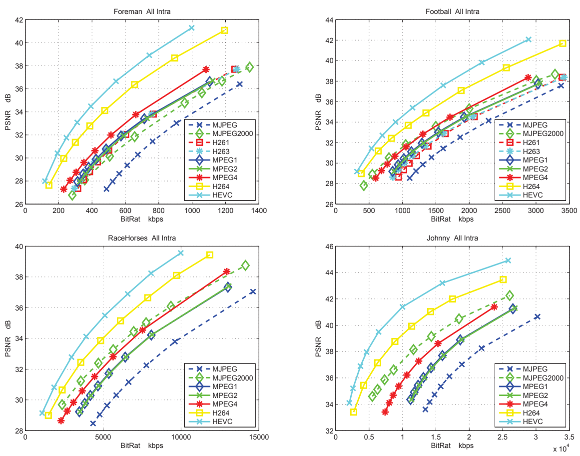

Fig. 6. RD curves for AI condition: From left to right, top to bottom: Foreman, Football, RaceHorses, Johnny.

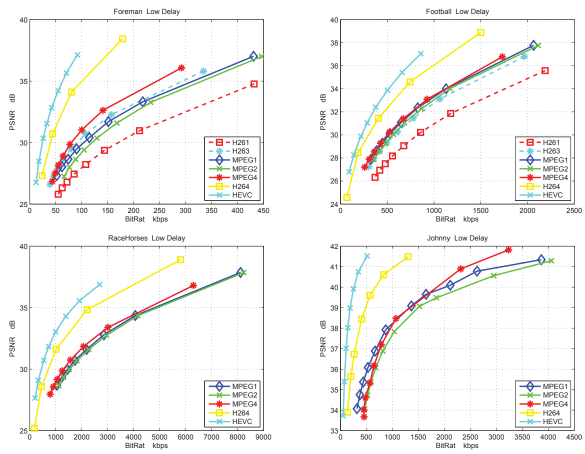

Fig. 7. RD curves for LD condition: From left to right, top to bottom: Foreman, Football, RaceHorses, Johnny.

From the simulation results, we can conclude that with the development of video compression techniques, the coding performance keeps improving and the latest video coding standards outperforms all of the previous video coding standards, especially for the sequences with high definition.

V. Conclusion

In this paper, an overview of existing image and video compression standards is presented. As for image coding standards, JPEG and JPEG 2000 are introduced and the comparison is given to show that both standards have their own advantages and enjoy popularity under certain circumstances. In addition, a brief discussion about MPEG-1, MPEG-2, MPEG-4, H.261, H.263, H.264/MPEG-4 AVC and HEVC is included to provide a review of video coding standards and their key features and applications. Experimental results show that every evolution of the coding algorithms contributes greatly the compression performance. This field is developing rapidly and its application can be found in various situations, and continuous effort on improving the coding algorithm will bring about a promising future for image and video compression.

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