Lossy and Lossless Intra Coding Performance Evaluation: HEVC, H.264/AVC, JPEG 2000 and JPEG LS

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***Abstract*—High Efficiency Video Coding (HEVC), the latest international standard of video coding under development, has shown a major breakthrough with regards to compression efficiency. But most of the currently published studies were intended to evaluate the overall R-D performance of HEVC in comparison to prior H.264/AVC video coding standard. In this paper, we present sufficient rate-distortion performance comparisons of image coding between the HEVC and previous image and intra-only video coding standards, including JPEG 2000, JPEG LS and H.264/AVC intra high profile. In addition, some recently reported performances of HEVC are also reviewed and compared. The coding simulations are conducted on a set of recommended video sequences during the development of the HEVC standard. Experimental results show that HEVC can offer consistent performance gains over a wide range of bitrates on natural video sequences as expected. Besides, we also present the comparison results of all these standards in the scenario of lossless image coding.**

I. Introduction

The ever-increasing availability of multimedia resources promotes the advancement of image and video coding algorithms. While it is widely accepted that, video coding algorithms, e.g. H.264/AVC [1], exploiting both the temporal redundancy between adjacent frames and spatial redundancy within a frame can achieve a higher compression efficiency than those algorithms designed only for images. There are some particular scenarios in which intra coding or image coding is the only choice, such as the editing within post-production where easy access to each individual frame is of great importance [2]. Further, the lossless intra coding is especially required for applications where images acquired are for extracting specific information in the future.

Currently, image coding can be realized mainly in two ways. One is to use coding algorithms aiming at images, JPEG2000 [3], JPEG-LS [4], etc. The other is by means of the intra mode of video coding algorithms, e.g. H.264/AVC.

At present, HEVC is the latest video coding algorithm under standardization[5]. Its prospective standard, which is expected to be accomplished in 2013, is very likely to become the next generation video coding standard following H.264/AVC. HEVC aims at doubling the compression ratio of H.264/AVC High profile with comparable image quality, at the expense of increased computational complexity. It is targeted at next-generation HDTV displays and can support display resolution from QVGA (320x240) up to 1080p (1920x1080) and 4320p (7680x4320) [6].

The main structure of HEVC is very similar to H.264. Both of them utilize the hybrid video coding schemes with spatial and temporal prediction, transform plus quantization of prediction error and entropy coding. The significant compression ratio improvement of HEVC comparing with H.264 is achieved by the refinement of various coding tools. In intra prediction of HEVC, more prediction modes for luma and chroma components are employed. In addition, the prediction can be performed in a larger range of block sizes. So it would be very meaningful to compare the performance of HEVC with other existing coding algorithms, such as H.264 and JPEG2000. The results will avail both researchers in this area and system designers aiming to balance performance gain and computational complexity.

Since the advent of H.264/AVC standard about ten years ago, many R-D performance comparisons have been performed between its intra-only lossy and lossless mode and other previous image compression standards like JPEG2000 and JPEGLS. Reviewing these literatures will help us to choose appropriate anchor and reasonable experiment settings for HEVC. A set of literatures have compared the performance on video test sequences. Smith et al. in [7] compared the JPEG2000 with H.264 FRExt Intra only mode on two RGB DCI clips with the resolution of 512 and 4K. The experiment shows that JPEG2000 significantly outperforms H.264 with I frames only for low bit rates, while H.264 has an advantage for high bit rates. Shi et al. in [8] perform an experiment on both DCI clips and low-resolution sequences and then draw a similar conclusion. Another consistent conclusion can also be found in [9]. In [10], Ouaret et al. conduct the Y component R-D performance comparison on 4:2:0 YUV sequences with resolution from QCIF to CIF. It concludes that for high spatial resolution sequences, JPEG2000 is competitive with AVC High Profile Intra with around 0.1 dB in PSNR in favor of AVC. While in low-resolution videos, JPEG2000 is outperformed by AVC. In [11] and [12], Topiwala et al.

do the comparison on 720p and 1080p YUV 4:2:0 sequences and the performance is evaluated on three color components separately. According to the results, H.264 is consistently advantageous in PSNR in luminance component for 720p, while as to the chroma components, JPEG2000 outperforms H.264 in low bit rate. For the 1080p the H.264 is still competitive with JPEG2000 in rate distortion sense. A similar conclusion can be drawn, when it comes to the RGB 1080p sequences in [13]. Meanwhile, in contrast with test video sequences, another set of literatures compare the performance of H.264/AVC high profile intra mode to JPEG2000 on selected test images. Their conclusions are summarized as follows. In [14], the two algorithms above are tested on 14 monochrome images and the R-D gains in the results are quite in favor of H.264. In [15], ten high definition images are tested and the conclusion is that JPEG2000 in most cases outperforms H.264/AVC. While in [13], six high-resolution RGB images are tested with the conclusion that JPEG2000 outperforms H.264 with a PSNR gap of around 2-3dB.

Despite the differences in video content, color space, resolution, bit depth and PSNR calculation method (using Y component or the average of three components), the conclusions drawn by testing video sequences are relatively consistent. The regulation can be summarized as follows: (1) JPEG2000 performs better on high-resolution sequences than on low-resolution sequences. (2) JPEG2000 has a better performance than H.264/AVC high profile intra mode in low bit rate situation. This can be proved by experiments in [7][8][9] and the chroma component performance in [11] and [12]. However, as there is no overall R-D performance analysis for all the three color components in [11] and [12], and only one resolution is covered in [13], the second regulation needs further proof. (3) According to the R-D performance, with the bit rate increasing, H.264/AVC performs much better than JPEG2000. It is very common that the performance advantage of JPEG2000 over H.264 decreases and finally be surpassed by H.264/AVC in high bitrate condition.

However, when comparing the two algorithms on selected images, the conclusions are contradictory. Results in [14] are totally in favor of H.264/AVC, while those of [13] and [15] are for JPEG2000. One major factor is the representativeness of those test images. The color space format, resolution, content of test images are selected relatively arbitrarily. Further more, the number of images included in each test sets is too small to ensure the validness of the results.

Another image based lossy case experiment is given in[16], where 34 images with three kinds of resolution are used to compare the image coding R-D performance among HEVC, H.264/AVC, JPEG2000, JPEG XR, WebP/VP8 and JPEG. The conclusion is that HEVC has an obvious advantage in all bit rates over the others. H.264/AVC and JPEG2000 rank second and third.

To overcome the limitations above, our experiment is designed with the following characters: (1) we test the competitors on the sequence set used in the standardization process of HEVC [17]. There are totally 24 sequences of 6 different kinds of resolutions ranging from 416x240 to 2560x1600. Except for two 10-bit sequences, bit depth of the rest sequences is 8bit. The content of sequences is more representative, including natural scene, artificial scene and computer software interface, etc. Each sequence contains hundreds of frames. Those factors cover a wide range of cases in image coding application so that they make the test results more convincing. (2)For the lossy test case, latest forerunners, H.264/AVC High Profile 4:4:4 intra mode and JPEG2000, are compared with the intra mode of HEVC main configuration and high10 configuration in a wide range of bitrates. This experiment is a complement of literatures mainly focused on the overall performance of HEVC, including both inter and intra predictions, compared with previous coding standards, such as [18][19]. It is also worth to mention JPEG XR[20]. Although it is the newest image coding standard, limiting computational resources and storage capacity requirements is under primary consideration. As a result, the R-D performance of JPEG XR cannot compete with that of JPEG2000 [21], so it is not compared in our experiment. (3) In addition, the lossless intra coding performance comparison is also taken into account in this paper. In [22], a more efficient sample-based angular prediction method for HEVC lossless coding is proposed.In [23], lossless coding is achieved on top of the lossy frame work by signaling the information lost in the lossy coding process. Their coding efficiency has been compared with previous lossless coding standards in [24], and a significant performance gain can be got by combining method [22] with [23]. However, the proposals above have not been accepted by the time we prepare this paper, so we are not able to include this in latter comparison. Besides the coding standards above, JPEG-LS, a standard intended for lossless and near lossless image coding, is also included.

The rest of the paper is organized as follows. For the self-consistency of this paper, a brief overview of the related codecs is provided in Section II. The detail information about test sequences, software implementation, parameter configuration and result evaluation method is specified in Section III. The experiment results and R-D performance analysis are presented in Section IV. Finally, Section V concludes the paper.

II. Overview of Compression Algorithms

In this section, we take a brief overview of the standardized coding algorithms related to our experiment, which are HEVC, H.264/AVC, JPEG2000 and JPEG-LS. The latter two are specially designed to encode still images, while the former two are video coding algorithms constrained to intra mode. The meaning of intra mode is that the algorithm only exploits spatial correlation information within an image and abandons the temporal prediction between adjacent frames.

A. HEVC

Up till now, the standardization process of HEVC is on going, and many of the coding algorithms adopted have still been improved progressively. So in this part, we only give the description about the state of the art intra prediction method.

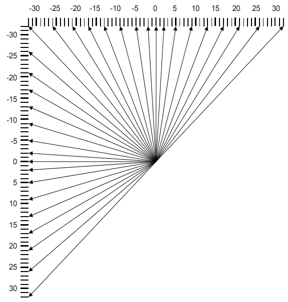

Fig. 1. 33 Intra Prediction Modes[26]

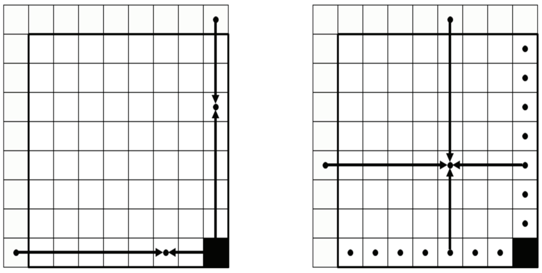

Fig. 2. Intra Planar Prediction Mode[26]

There are mainly three kinds of intra prediction mode for luminance component, including Intra_DC, Intra_Angular and Intra_Planar. [25]

For Intra_DC method, the basic idea is to use the mean value of surrounding pixels to predict the current encoding region.

Intra_Angular model is a much finer prediction method than H.264/AVC to accurately represent the directional structures within the block to be encoded. There are as many as 33 predict directions in it.

For Intra Planar method, it is designed to predict smooth image regions in a visually friendly way. It provides maximal continuity of the image plane at the block borders and follows the gradual changes of the pixel values. When a block is coded in planar mode, its bottom-right sample is signaled in the bit stream. The rightmost and bottom samples of the blocks are linearly interpolated, and the middle samples are bilinearly interpolated from the border samples. [26]

B. H.264/AVC

The intra coding algorithm of H.264/AVC includes four main steps, spatial prediction, transform, scalar quantization and entropy coding.

In H.264/AVC main profile, there are 9 prediction modes for 4x4 block based luminance spatial prediction, 4 modes for 16x16 block based luminance spatial prediction and 4 modes for 8x8 block based chrominance spatial prediction. In High 4:4:4 profile, nine kinds of 8x8 spatial prediction modes are added to intra algorithm.

The predicted block is subtracted from the original block, generating the residuals. In H.264/AVC main profile, a multiplication-free, separable integer transform based on a 4x4 block size is applied. This design relieves some unpleasant subjective artifacts and solves the mismatch problem as well. The high profile encoder or the so-called AVC Fidelity Range Extensions (FRExt) extends the transform section by adding an 8x8 integer transform, which enables the preservation of fine details and textures which generally require larger basis functions. In addition, the algorithm also allows the adaptive selection between the 4x4 and 8x8 integer transforms for further improvement of coding efficiency. The addition of 8x8 transform is very beneficial for high resolution high bit rate applications.

To quantize the transformed residuals, H.264/AVC uses no-uniform scalar quantization method. For each macroblock, there are 52 quantization parameter (QP) values for selection. Prior to entropy coding, the quantized transform coefficients of a block are scanned in a zigzag order.

An efficient method for lossless coding in H.264/AVC is sample-by-sample differential pulse code modulation (DPCM)[27][28]. The core algorithm of lossless coding capability is based on [27]. According to that, the transformation and quantization steps are all bypassed, and each sample is predicted by a neighboring pixel in the direction determined by the prediction mode. The residuals are then directly entropy coded.

There are two kinds of entropy coding methods in H.264/AVC, the Context-Adaptive Variable Length Coding (CAVLC) and Context-Adaptive Binary Arithmetic Coding (CABAC). In our experiment, CABAC is used. As an arithmetic coder, CABAC can assign each symbol of the alphabet with a non-integer number of bits and outperforms the VLC tables as a result.

Furthermore, H.264/AVC High Profile offers additional features like lossless coding and the support for up to 14 bits per sample in High 10 Intra, High 4:2:2 Intra, High 4:4:4 Intra, CAVLC 4:4:4 Intra and High 4:4:4 Predictive Profiles.[29][30]

C. JPEG2000

The JPEG2000 image coding algorithm consists of 5 parts, Pre-Processing, Discrete Wavelet Transform (DWT), Uniform Quantizer with Dead zone, Adaptive Binary Arithmetic Coder and Bit-stream Organization.

The preprocessing part includes three functions, image tiling, DC level shifting and component transformations. The term tiling refers to the partition of the original image into rectangular nonoverlapping blocks, which are compressed independently as if they were totally distinct images. Before the computation of the forward discrete wavelet transform (DWT) for each image tile, all samples in a image tile component are applied with a dc level shift by subtracting the same quantity 2^{p-1}, where P is the precision of components. The standard supports two component transformations, the irreversible component transformation (ICT) that can be used for lossy coding and the reversible component transformation (RCT) that may be used for both lossless and lossy coding. In addition, direct encoding without color component transformation is also supported.

Discrete wavelet transform is used to process the tile components into different decomposition levels. These levels include a number of subbands with coefficients describing horizontal and vertical spatial frequency characteristics of the original tile component.

After the transformation, all coefficients are quantized using the uniform scalar quantization with dead-zone. The precision of coefficients is reduced in this process and is usually lossy.

Entropy coding is implemented with an arithmetic coding system that compresses binary symbols relative to an adaptive probability mode related to each of 18 different coding contexts. JPEG2000 uses a very restricted number of contexts for any given type of bit. This allows rapid probability adaptation and decreases the cost of independently coded segments.

Finally, the output of the arithmetic encoder is organized as a compressed bit-stream. [31]

As with Motion-JPEG2000, it is as Part 3 of the JPEG2000 image coding standard and is based on the core coding technology of the baseline JPEG2000 Part 1.[32]

D. JPEG-LS

JPEG-LS (Joint Photographic Experts Group C Lossless Standard) is an ISO/ITU standard for lossless and near-lossless compression of continuous-tone images [4]. The core algorithm of JPEG-LS consists of two independent and separated stages called modeling and coding.

The modeling stage contains three phases mainly. First, the gradients corresponding to different types of image samples, flat part or image part, are calculated. Second, the predictor is applied for de-correlation in condition that the procedure enters the regular model. Otherwise, the process enters the run model for more efficient coding. At last, the context modeler is used for adaptive prediction.

The coding stage contains two kinds of codes, Golomb codes and run length codes. For data with a geometric distribution, they have the Golomb code as an optimal prefix code. It makes Golomb codes very suitable for situations when small values in the input stream occur more frequently than large values. To avert the excess code length over the entropy, which is a defect for Golomb codes in smooth region, alphabet extension is used by taking codes blocks of symbols instead of coding individual symbols. This is the run mode [33].

III. Evaluating Methodology

The test sequences used in our experiment are the same as those used during the standardization process of HEVC, as in Table I. The primary reason for us to choose this data set is its good representativeness. The wide coverage of resolution, additional 10bit sequences, sufficient number of frames and typical sequence content make it offer a good simulation of common coding scenarios. Thus, it can be expected to provide more convincing test results.

A. Codec Settings

In this codec performance comparison, publicly available software implementations of HEVC, H.264/AVC, JPEG2000 and JPEG-LS are used for the experiment.

For HEVC, the latest release of the reference software (HM 7.0) [34] is used for HEVC main profile and high10 configuration encoder, and each frame in the test sequences is coded in the intra coding mode.

The configuration of the HEVC HM7.0 main profile encoder is consistent with the file encoder_intra_main.cfg which is a configuration file of the software. The detail is as table II.

The setting of HM high10 configuration encoder is consistent with the file encoder_intra_he10.cfg. Most of the settings are the same as that of main profile, except for the items in table III.

When the entry LosslessCuEnabled is set to 1 and item QP is set to 0, both the main profile encoder and high10 configuration encoder turn into the lossless encoder without further changes. 8 bit sequences are encoded according to main profile lossless configuration, while 10 bit sequences are encoded as the high10 lossless configuration.

For H.264/AVC, the latest release of the reference software (JM 18.3) [35] is used for H.264/AVC FRExt High 4:4:4 Profile.

The configuration of the High 4:4:4 Profile encoder is in Table IV.

The configuration of lossless coding model is the same as that of above, except that the item LosslessCoding is set to 1 and the item QPISlice is set to 0. For 8 bit sequences, both the input and output bit depth are set to 8, while for 10 bit sequences, the items above are set to 10.

For JPEG2000, we use motion JPEG2000 to encode video test sequences. The software implementation is based on OpenJPEG v1.4 [36]. The configuration is as default.

For JPEG-LS, we use JPEG-LS reference encoder v1.00 [37]and the configuration is just as its default model.

TABLE I
Test Sequences Information

Sequence Name	Resolution	Bit Depth	Frame Count
Traffic	2560x1600	8	150
PeopleOnStreet	2560x1600	8	150
Nebuta	2560x1600	10	300
SteamLocomotive	2560x1600	10	300
Kimono	1920x1080	8	240
ParkScene	1920x1080	8	240
Cactus	1920x1080	8	500
BQTerrace	1920x1080	8	600
BasketballDrive	1920x1080	8	500
RaceHorses	832x480	8	300
BQMall	832x480	8	600
PartyScene	832x480	8	500
BasketballDrill	832x480	8	500
RaceHorses	416x240	8	300
BQSquare	416x240	8	600
BlowingBubbles	416x240	8	500
BasketballPass	416x240	8	500
FourPeople	1280x720	8	600
Johnny	1280x720	8	600
KristenAndSara	1280x720	8	600
BaskeballDrillText	832x480	8	500
ChinaSpeed	1024x768	8	500
SlideEditing	1280x720	8	300
SlideShow	1280x720	8	500

B. Evaluating Criteria

The overall encoding performance is synthesized from the PSNR of luma component and two chroma components, as it is in [18].

$$PSNR_{avg} = (6 * PSNR_Y + PSNR_U + PSNR_V)/8 \quad (1)$$

It is noted that these results are still based on PSNR measurements, which are an imperfect substitute for subjective quality assessment, and that the subjective performance of corresponding results may actually be generally somewhat better than its objective (PSNR) performance may indicate [18].

The final PSNR of a sequence in a given bitrate is the average result of PSNRavg for each frame.

IV. Experimental results

A. Lossless Coding Comparison

The lossless coding results of HEVC intra mode, H.264/AVC High 4:4:4 Profile intra mode, MJPEG2000 and JPEG-LS are listed and compared in Table V, including original file size of test sequences, compressed file size and compression ratio of corresponding sequences for each coding standard. The unit of all the file size is byte. The compression ratios are calculated as follows

For 8 bit sequences, the compression ratio can be derived by means of dividing original file size by compressed file size. While for 10 bit sequences, the compression ratio is derived by dividing original file size by compressed file size and then multiplying the intermediate result by index 0.625. This index is the result of 10/16, which is related to ratio of valid data contained in original YUV file. Because YUV files use two bytes to store one pixel of a 10 bit sequence, only ten bits in every two bytes are meaningful.

TABLE II
Test Condition of HM7.0

item	value
MaxCUWidth	64
MaxCUHeight	64
MaxPartitionDepth	4
QuadtreeTULog2MaxSize	5
QuadtreeTULog2MinSize	2
QuadtreeTUMaxDepthIntra	3
IntraPeriod	1
GOPSize	1
RDOQ	1
LoopFilterDisable	1 (enabled)
InternalBitDepth	8
SAO	1

TABLE III
Configuration Supplement of High10

item	value
InternalBitDepth	10
ALF	1
LMChroma	1
NSQT	1
TS	1

Although the core algorithms of the four coding standards are different, there still exists some common regulations according to the results. (1) The first is that, for 8 bit sequences, sequences with higher resolution tend to achieve better compression performance. This can be proved by averaging the compression ratio with the same resolution and then comparing the difference between them. The corresponding results are consistent with the regulations above for all the first 17 sequences in Table I. (2) As to the rest 7 sequences, their performance reveals some major factors, such as simple and regular texture and widely existed smooth area, of video content that will influence the overall compression behavior. Taking sequence Johnny as an example, most part of the background consists of smooth area with almost identical color and very few details. While for the foreground, the man, the texture structure of clothes and face is very regular and of much redundancy, so that the intra predict method can cover most of image content and leave very little residual. (3) The coding performance of 10 bit sequences is inferior than that of 8 bit sequences.

Comparing the performances between the four coding standards, four competitors can be divided into two groups. The first includes JPEG-LS and MJPEG2000, and the second contains H.264/AVC and HEVC. The performance of the first group outperforms the second in all bit rates. While in the first group, the results are in favor of JPEG-LS for most of the sequences. In the second group, the compression efficiency of HEVC and H.264/AVC is very similar to each other. One reasonable explanation is that the standardization process of HEVC is not completed, the algorithm design and implementation of lossless coding is not finished. This causes that the performance gain of finer angular intra prediction in HEVC is compensated by the pixel wise DPCM [27] in H.264/AVC lossless intra coding mode. A very efficient sample-based angular lossless intra prediction algorithm has been proposed in [22], while the acceptance of it is still under consideration when the paper is being prepared.

B. Lossy Coding Comparison

Fig. 3 to Fig. 4 depict the rate-distortion performance of each coding standard on test video sequences.

The results above are very consistent for all test sequences except SlideShow that intra mode performance of HEVC high10 configuration outperforms HEVC main profile in all bit rates, and HEVC main profile outperforms H.264/AVC in all bit rates. For Motion JPEG2000, it outperforms HEVC

TABLE IV
Test Condition of JM18.3

item	value
ProfileIDC	244(High 4:4:4)
FastCrIntraDecision	1(enable)
CbQPOffset	0
Transform8x8Mode	1
SymbolMode	1(CABAC)
RDOptimization	1(enabled)
DFDisableRefISlice	0(enabled)

TABLE V

EXPERIMENT RESULT OF LOSSLESS CODING

Sequence	Original File Size	HEVC Comprized size/Ratio	H.264 Comprized size/Ratio	MJPEG2000 Comprized size/Ratio	JPEG-LS Comprized size/Ratio
NebutaFestival	3686400000	1792400968/1.29	1850038897/1.25	1484205741/1.55	1501318406/1.53
SteamLocomotiveTrain	3686400000	1220365991/1.89	1196366138/1.93	1067532663/2.16	1080373836/2.13
PeopleOnStreet	921600000	416174504/2.21	402780791/2.29	368230959/2.50	341163050/2.70
Traffic	921600000	425740795/2.16	405005845/2.28	375993577/2.45	360097310/2.56
BasketballDrive	1555200000	709471654/2.19	705352270/2.20	689578697/2.26	679536451/2.29
BQTerrace	1866240000	976532345/1.91	1056591524/1.77	942419228/1.98	935395858/2.00
Cactus	1555200000	803328559/1.94	840199039/1.85	764457189/2.03	756385786/2.06
Kimono1	746496000	321112072/2.32	317451296/2.35	289465867/2.58	287887166/2.59
ParkScene	746496000	379919451/1.96	387349363/1.93	344571618/2.17	338920547/2.20
BasketballDrill	299520000	142667474/2.10	157041705/1.91	145095150/2.06	137334426/2.18
BQMall	359424000	172589463/2.08	174963229/2.05	166118478/2.16	158884990/2.26
PartyScene	299520000	181429861/1.65	215769749/1.39	174480464/1.72	167585435/1.79
RaceHorses	179712000	89778782/2.00	99005714/1.82	81504121/2.20	79138110/2.27
BasketballPass	74880000	34893199/2.15	34369816/2.18	32113798/2.33	29637954/2.53
BlowingBubbles	74880000	46964393/1.59	56369589/1.33	44969089/1.67	43154085/1.74
BQSquare	89856000	53139081/1.69	63243986/1.42	52126625/1.72	49178009/1.83
RaceHorses	44928000	24150806/1.86	26884827/1.67	21661992/2.07	21001665/2.14
FourPeople	829440000	325683153/2.55	314061925/2.64	293812535/2.82	276826215/3.00
Johnny	829440000	298279721/2.78	290765133/2.85	277766852/2.99	265939169/3.12
KristenAndSara	829440000	297257619/2.79	289684532/2.86	276375517/3.00	259785016/3.19
BasketballDrill	299520000	139803155/2.14	153765855/1.95	144432390/2.07	135431844/2.21
ChinaSpeed	589824000	196556195/3.00	182802029/3.23	206665379/2.85	177983065/3.31
SlideEditing	414720000	111224412/3.73	109101491/3.80	140670717/2.95	102833645/4.03
SlideShow	691200000	74694982/9.25	69586220/9.93	78617186/8.79	66174555/10.45

high10 configuration, HEVC main profile and H.264/AVC High Profile 4:4:4 in low bit rates. When it comes to high bit rate, the performance is surpassed by H.264/AVC and two configurations of HEVC.

The performance comparison between HEVC and H.264/AVC has been widely researched. Confident conclusion has been drawn and is consistent with the results above.

The performance comparison between H.264/AVC High-Profile and JPEG 2000 on high resolution test sequences has also been researched. The conclusions consistent with our results can be found in [7][8][9].

When the comparison with HEVC is added, the advantage of Motion JPEG2000 is still reasonable. The reasons are as follows. The first is related to the superiority of wavelet transform. The inter pixel correlation increases with the increase of resolution, so image content is smoother in high resolution sequences than that in low resolution ones. As HEVC still uses block based DCT transform, so wavelet-based Motion JPEG2000 encoder can still hold better decorrelating properties of wavelet transform in largely smooth image areas [38]. Meanwhile, quantization in low bit rate can aggravate the range of smooth areas. The two factors above contribute to the low bit rate advantage of Motion JPGE2000 in both high and low resolution sequences. The second reason is related to the simplicity of chroma intra predict method. The PSNR index in our experiment is a linear combination of the PSNR in luma and two chroma components. As in [12], R-D performance of Motion JPEG on chroma components surpasses the H.264/AVC obviously in low bit rate. The relative simpler intra prediction method of chroma component makes the R-D performance less competitive than luma component, which contributes to the low bit rate disadvantage of H.264. While in the latest released software implementation of HEVC, the chroma component intra prediction is still less complex than that of luma, so it is reasonable to speculate that the low bit rate advantage of Motion JPEG2000 still holds. The gap can only be compensated when bit rate is high and the superiority of luma intra prediction is fully developed.

The only exception occurs when our experiment is tested on sequence SlideShow. As the content of the sequence is so simple that most of the area is smooth and with the same color. In this condition, the decorrelation superiority of wavelet transform is dominant, so that many frames can be losslessly encoded with relative low bit rate. As a result, the R-D performance transcends the rest three in a great degree.

It is also worth mentioning that there are some important differences in testing conditions which lead to different results between ours and that of [16]. The first different is that more than 60% of test sequences in our experiments are in high resolution, while less than 24% of the test images in [16] are in high resolution. The experiment results are represented in different ways. In our experiment, the PSNR of luma and chroma components are first linearly combined, and then the R-D performance between different coding standards are compared. While in [16], the BD-BR [39] metric is used to give an overall evaluation of individual coding standards, and the luma component and chroma components are compared separately. So the there are no substantial contradictions between the two experiments.

V. CONCLUSION

The study in our paper mainly focuses on the coding environment where only the spatial correlation within an image

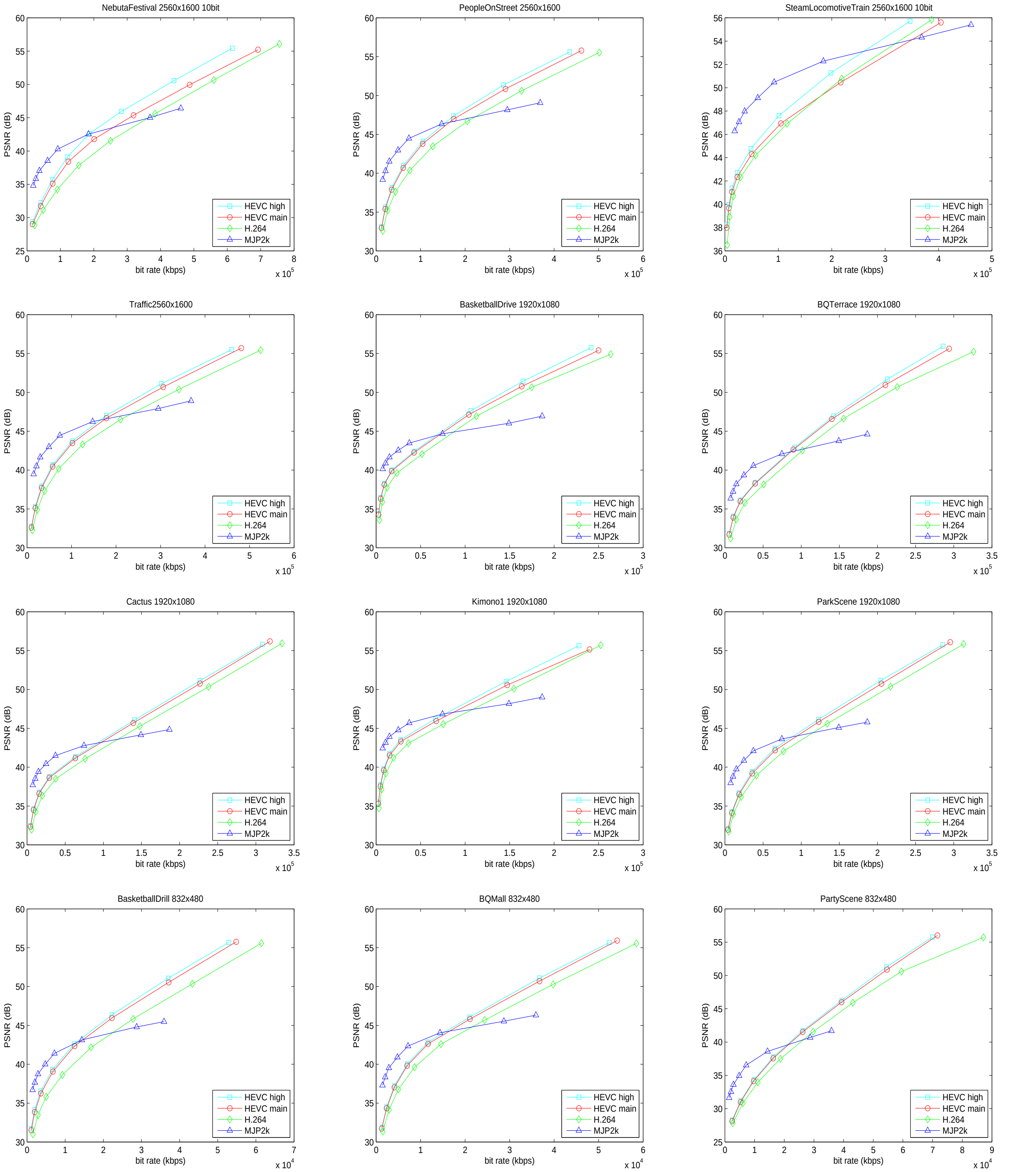

Fig. 3. R-D performance of HEVC main profile, HEVC high10 configuration, H.264/AVC High-Profile 4:4:4 and Motion JPEG 2000 on sequences, *NebutaFestival,PeopleOnStreet, SteamLocomotiveTrain, Traffic, BasketballDrive, BQTerrace, Cactus, Kimono1, ParkScene, BasketballDrill, BQMall and PartyScene*

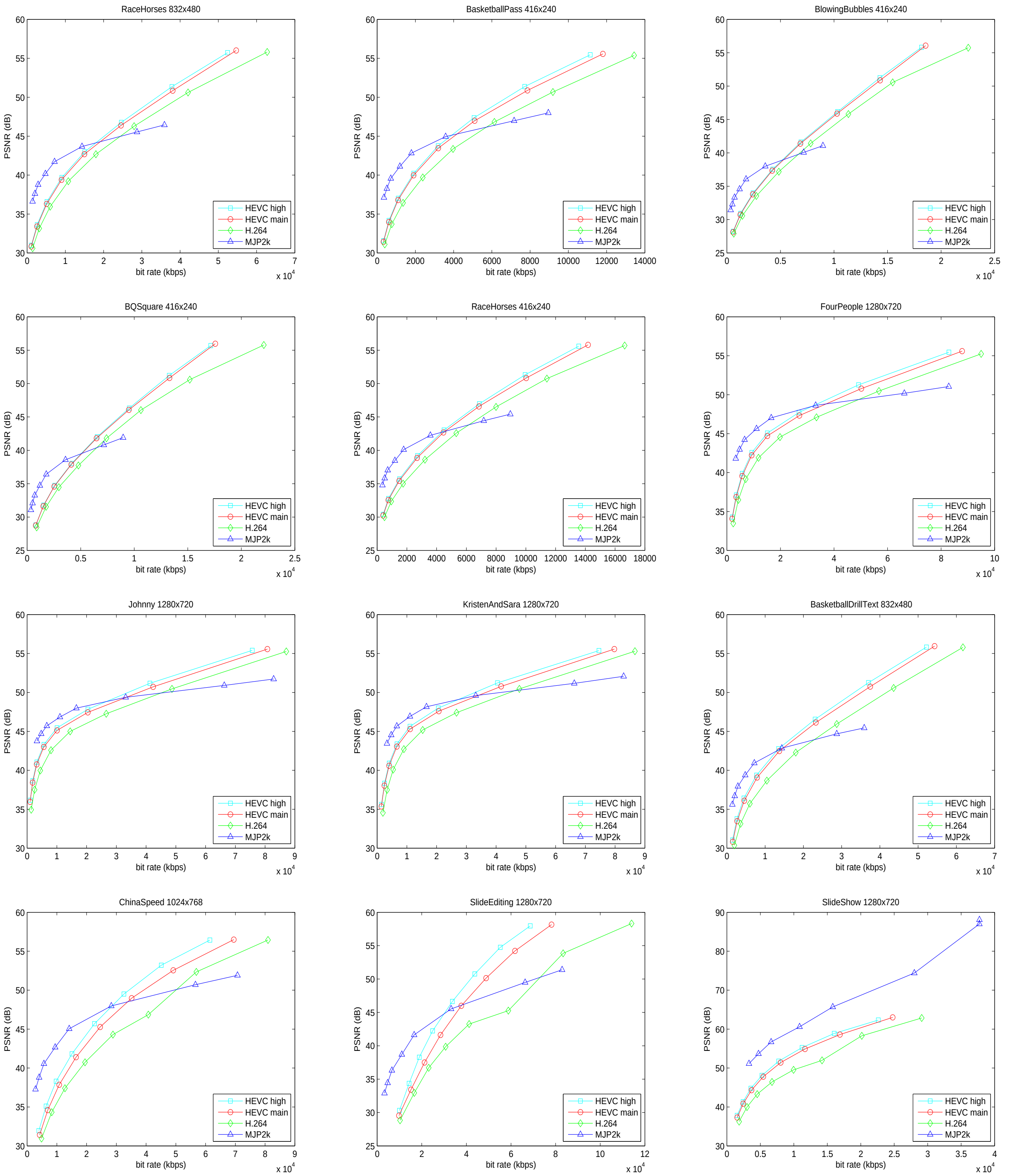

Fig. 4. R-D performance of HEVC main profile, HEVC high10 configuration, H.264/AVC High-Profile 4:4:4 and Motion JPEG 2000 on sequences, *RaceHorses, BasketballPass, BlowingBubbles, BQSquare, RaceHorses, FourPeople, Johnny, KristenAndSara, BasketballDrillText, ChinaSpeed, SlideEditing and SlideShow*

can be exploited. The experiments are done on a video test sequence set for the standardization process of HEVC, which represents the common coding applications very well.

First, a lossless coding performance comparison between HEVC, H.264/AVC High-Profile 4:4:4, Motion JPEG2000 and JPEG-LS is conducted. The conclusion is that the lossless intra coding performance of HEVC has matched that of H.264/AVC and is also comparable to JPEG-LS and JPEG2000.

Second, a lossy intra coding performance comparison among HEVC main profile, HEVC high10 configuration, H.264/AVC High-Profile 4:4:4 and Motion JPEG2000 is conducted. The results prove again the ascending coding efficiency from H.264/AVC and HEVC main profile to HEVC high10 configuration. In addition, Motion JPEG2000 outperforms the former three in low bit rate performance, while this advantage is gradually compensated and finally surpassed by the former three as the bit rate increases.

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