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ITP Colour Space and Its Compression Performance for High Dynamic Range and Wide Colour Gamut Video Distribution

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Abstract

High Dynamic Range (HDR) and Wider Colour Gamut (WCG) content represents a greater range of luminance levels and a more complete reproduction of colours found in real-world scenes. The current video distribution environments deliver Standard Dynamic Range (SDR) signal Y′CbCr. For HDR and WCG content, it is desirable to examine if such signal format still works well for compression, and to know if the overall system performance can be further improved by exploring different signal formats. In this paper, ITP (IC_TC_P) colour space is presented. The paper concentrates on examining the two aspects of ITP colour space: 1) ITP characteristics in terms of signal quantization at a given bit depth; 2) ITP compression performance. The analysis and simulation results show that ITP 10 bit has better properties than Y′CbCr-PQ 10bit in colour quantization, constant luminance, hue property and chroma subsampling, and it also has good compression efficiency. Therefore it is desirable to adopt ITP colour space as a new signal format for HDR/WCG video compression.

Keywords

HDR; WCG; Y′CbCr; ITP; IC_TC_P

1 Introduction

Current video distribution environments deliver a Standard Dynamic Range (SDR) signal. For SDR content, the common practice is to apply compression on a non-constant luminance (NCL) Y′CbCr colour difference signal defined in ITU-R BT.709 [1] using a gamma transfer function (ITU-R BT.1886 [2]) and non-constant luminance 4:2:0 chroma subsampling. With the advance of display technologies, commercial interests in High Dynamic Range (HDR) and Wide Colour Gamut (WCG) content distribution are growing rapidly. Compared with conventional SDR content, HDR/WCG video content has a greater range of luminance levels and colours found in real-world scenes, and this creates a more pleasant, immersive viewing experience for people with advanced HDR displays. In order to deliver the HDR/WCG content, an HDR/WCG video distribution workflow has to be employed from content creation to final display, which comprises of post-production, encoding, transmission, decoding, colour volumn mapping and display. It is desirable to have a signal format for HDR and WCG content that is not only suitable for efficient image signal encoding, but also suitable for video compression and colour volume mapping. Therefore, for HDR/WCG content distribution, we can examine whether the conventional Y′CbCr 4:2:0 NCL signal format is still a good format to represent HDR/WCG video, and if it still compressed well by a video codec developed using SDR content. In this paper, the main focus is on compression related part (the encoding and decoding blocks) in the distribution pipeline.

MPEG is the working group formed by ISO and IEC to create standards for video and audio compression and transmission. In July 2013, MPEG started to look into the problem at the request of several studios and consumer electronics companies [3]. An Ad-Hoc Group (AhG) on HDR and WCG was established to investigate if any changes to the state-of-the-art High Efficiency Video Coding (HEVC) standard [4] are needed for HDR/ WCG video compression. For applications such as Ultra HD Blu-ray disk, it is mandatory that HDR content is transmitted using the HEVC Main 10 profile with metadata in VUI and SEI message [5]. This is commonly referred to as the “HDR-10” solution [6]. The HDR-10 essential metadata includes the signaling of the following video characteristics: SMPTE ST 2084 HDR Perceptual Quantizer transfer function (PQ-TF), ITU-R BT. 2020 [7] colour primary, and Y′CbCr non-constant luminance in ITU-R BT. 2020. In this paper, the signal format in HDR-10 is referred to as Y′CbCr-PQ 10bit. Other than defining some metadata to represent different video characteristics, "HDR-10" follows closely the common practice of SDR distribution which uses the gamma transfer function, ITU-R BT.709 colour primary, and Y′CbCr non-constant luminance in BT.709.

After several rounds of tests and demonstrations, the MPEG HDR/WCG AhG concluded that, for applications that use high bitrate compression, such as the Blu-Ray application, the performance of "HDR-10" seems to be sufficient. For applications that need compression at lower bitrates, such as broadcast and over-the-top (OTT) applications, several shortcomings of "HDR-10" were discovered, suggesting that further improvement might be necessary. In February 2015, MPEG issued a Call for Evidence (CfE) [8] to look for solutions that improve the HDR/WCG video coding performance over HEVC Main 10. A set of anchors targeting broadcast/OTT bitrates are provided using the HEVC Main 10 codec with ST 2084 [9] and ST 2086 support [10]. Anchors generated this way closely model the "HDR-10" distribution system.

As active participants of the MPEG committee work on HDR/WCG coding, Arris, Dolby, and InterDigital submitted a joint proposal (the ADI solution) [11] in response to the CfE. The joint proposal provides evidence that with a few new technologies: 1) ITP (IC_TC_P) colour space; 2) colour enhancement filter; and 3) adaptive reshaping and transfer function, the coding performance can be further improved for HDR/WCG content [12].

This paper mainly focuses on the ITP colour space. The paper tries to answer two questions: 1) what is ITP? Compared to Y′CbCr-PQ, what is advantage of using ITP? 2) How does ITP work for compression?

The paper is organized as follows. Section 2 describes ITP colour space. Section 2.1 describes ITP conversion workflow. Section 2.2 presents ITP properties. Section 3 presents ITP compression performance for HDR and WCG video compression followed by conclusion in Section 4.

2 IPT Colour Space and ITP (IC_TC_P) Colour Space

Non-Constant Luminance (NCL) Y′CbCr is the most frequently used colour space for the distribution of SDR signals. Y′CbCr is a colour difference model derived from nonlinear R′G′B′ signals. For HDR signals, the ST. 2084 (also known as PQ) transfer function is applied in linear RGB space. NCL Y′CbCr has some limitations: 1) it cannot fully de-correlate intensity information from chroma information; 2) it is constrained by RGB colour primaries; therefore, the 3x3 matrix coefficients keep on changing according to RGB colour primaries; 3) its colour difference weights are not based on perceptual model but are derived by filling a colour volume. Constant Luminance (CL) Y′CbCr was added in ITU-R BT. 2020 to adjust Y′CbCr to better de-correlate intensity from chroma. However, the conversion is significantly more complex, making it harder to use in real applications. The IPT colour space is an alternative colour space to de-correlate intensity and chroma information better matching the perceptual mechanisms of the Human Visual System (HVS) [13]. This alternate colour space is more advantageous for HDR and WCG video than the NCL Y′CbCr in signal representation. The advantage of using HVS to derive such a colour space is that the distortion introduced is perceptually minimized.

2.1 ITP Conversion Flow

IPT uses a colour opponent model which has similar conversion flow to NCL Y′CbCr but more closely mimics the HVS. I corresponds to brightness of the pixel nonlinearly encoded (similar to how the Y′ is encoded in Y′CbCr), T corresponds to blue-yellow colour perception and P corresponds to red-green colour perception. IPT was first introduced in 1998 and was optimized using a limited set of training data with standard dynamic range and BT. 709 colour gamuts due to the lack of HDR/WCG content at that time [14]. The proposed ITP colour space improves the original IPT by exploring higher dynamic range (up to 10000 nits) and larger colour gamuts (BT. 2020). Considering the non-trivial changes over the original IPT and to follow the Y′CbCr practice to have blue-related colour component prior to red-related colour component, the new name ITP or IC_TC_P colour space is adopted to refer to this variation of the original IPT colour space.

To better understand ITP, the early stages of human colour vision are described as follows (**Fig. 1**) [13]:

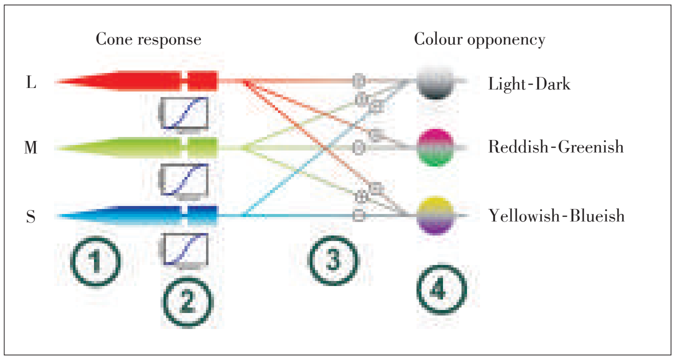
1) Incoming light strikes the three photo receptors (cones) in the eye that have their peak sensitivity in the (L)ong, (M)edium, and (S)hort wavelengths;
2) This linear light is transduced (converted) into a non-linear signal response to reduce dynamic range;
3) The non-linear output goes through a colour differencing process to extract important information and separates the signal into three distinct pathways;
4) The brain sees three colour opponent channels.

ITP conversion steps (**Fig. 2**) are as follows:

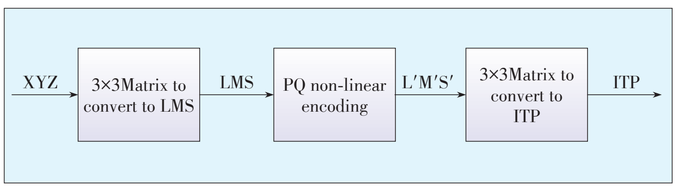
1) Compute LMS response;
2) Apply non-linear encoding PQ;
3) Apply colour differencing equation.

The similar complexity of the conversion as Y′CbCr allows mass deployment in a wide range of devices. Essentially the existing devices can just change the 3x3 matrix.

The conversion matrix from the CIE XYZ tri-stimulus values to LMS (derived RGB_{2020} to LMS) and LMS to ITP are listed below. Equ. (1) shows the Conversion from XYZ to LMS colour space, (2) shows the Conversion from RGB_{2020} to LMS colour space, and (3) shows the Conversion from L′M′S′ to ITP colour space. Note that the coefficients in the conversion matrices shown in this paper are the rounded decimal representation of the real conversion matrices. They may have higher precision



▲Figure 1. Opponent colour model in HVS.



▲Figure 2. XYZ to ITP conversion.

or fixed point representation depending on implementation needs.

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} 0.3592 & 0.6976 & -0.0358 \\ -0.1922 & 1.1004 & 0.0755 \\ 0.0070 & 0.0749 & 0.8434 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} 0.4120 & 0.5239 & 0.0641 \\ 0.1667 & 0.7204 & 0.1129 \\ 0.0241 & 0.0755 & 0.9004 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} I \\ P \\ T \end{pmatrix} = \begin{pmatrix} 0.5000 & 0.5000 & 0.0000 \\ 1.6137 & -3.3234 & 1.7097 \\ 4.3780 & -4.2455 & -0.1325 \end{pmatrix} \begin{pmatrix} L' \\ M' \\ S' \end{pmatrix} \tag{3}$$

2.2 ITP Properties

When designing a colour space, the main goal is to minimize colour distortion and prevent visible quantization artifacts when images are represented with a given number of digital codewords (i.e., given bit depth). Another requirement is to decorrelate the chroma information from luma information to enable colour subsampling, which is important for video compression. In the context of HDR and WCG, and due to various displays in market which supports different dynamic range and colour gamut, a colour space should fit for colour volume mapping as well. In the following, a set of psychophysical experiments have been conducted to validate the advantages of ITP over Y′CbCr-PQ for HDR and wide-gamut imaging. Compared with Y′CbCr-PQ, ITP has the following properties:

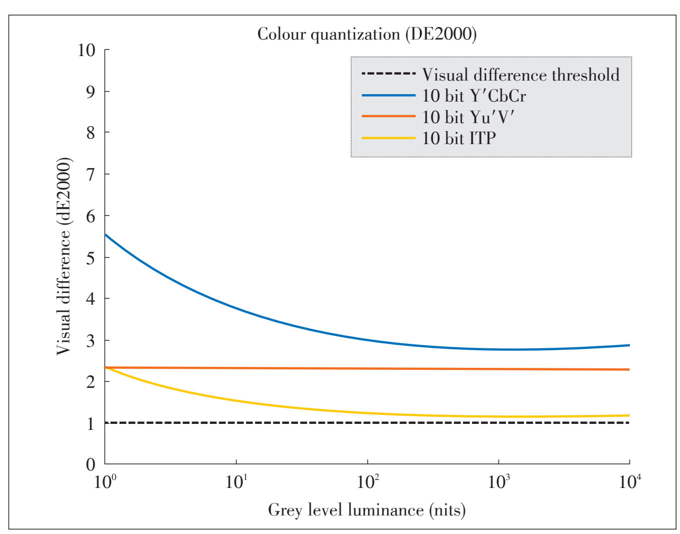
1) Better signal representation (smaller just-noticeable-difference) in colour quantization in 10 bits;
2) Improved intensity prediction (constant luminance);
3) Better predicted lines of constant hue for worst case;
4) Friendliness to 4:2:0 chroma downsampling.

2.2.1 Baseband Property in Colour Quantization

Baseband signal encoding refers to the representation of a linear light HDR signal in integer codewords in a given bit depth. Ideally, the higher the bit depth, the easier the quantized signal can preserve the dynamics in the original linear light signal. However, due to practical considerations, the highest existing pipeline for broadcast is limited to 10 bits. So it is very important to investigate how good ITP 10 bit baseband property can be. It decides how good the signal can start with and thus impact the full chain performance of HDR and WCG content distribution. Mathematical computation shows that ITP has the best overall baseband performance compared with Y′CbCr and Yu′v′ when quantized to 10 bits (**Fig. 3**). The industry accepted DE2000 metric is used to measure the visual difference. If the value is below the detection threshold of one "just noticeable difference" JND, no noticeable colour quantization artifact can be observed. The value of dE2000 for Y′CbCr-PQ 10b is between 3.0 and 5.5. For Yu′v′-PQ, it is 2.3. For ITP, it is about 1.0 above 100 nits which is the JND threshold. The better colour quantization property of ITP is due to the fact that ITP is more perceptually uniform than the other colour spaces [15].

2.2.2 Constant Luminance Property

Constant luminance encoding is more effective in reducing crosstalk between luma and chroma components than the conventional NCL encoding method. Therefore, a colour space which has better constant luminance property tends to have better chroma downsampling, such as 4:2:0. Both subjective experiment and theory shows that ITP outperforms NCL Y′CbCr in intensity prediction. In the subjective experiment, 11 participants matched the intensity of a colour patch with a reference



▲Figure 3. Visual difference of colour space.

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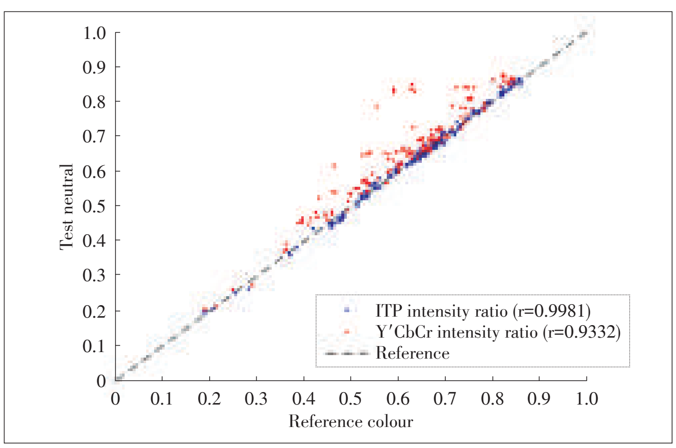
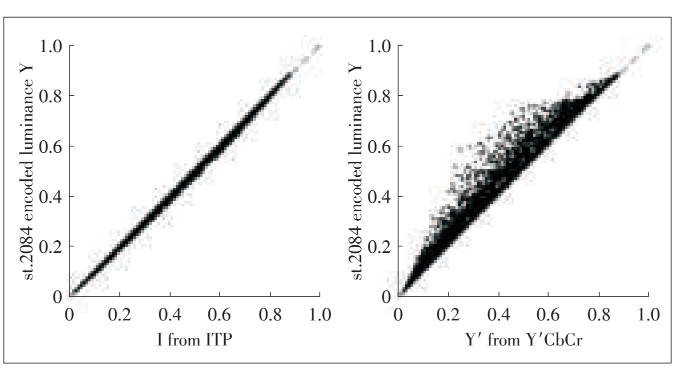
neutral. The data gathered was used to test various colour spaces. ITP outperforms NCL Y′CbCr in intensity prediction (indicated by the higher correlation to the reference) (**Fig. 4**). The property is also validated in scientific analysis, where uniformly distributed RGB samples are generated and is converted in ITP, NCL Y′CbCr and CL Y′CbCr, and the correspondence is shown in **Fig. 5**. The I in ITP correlates better with constant luminance Y′ than the NCL Y′ from Y′CbCr.

2.2.3 Hue Property

For colour volume mapping, since observers perceiving changes in hue is more impactful than changes in lightness or chroma, it is desirable to have a colour space as hue-linear as possible. Linear hue lines make it very easy to model the mapping process with the hue-preservation requirement. ITP was designed for linear hue property, so it has better hue linearity. A psychophysical experiment was conducted to determine lines of constant hue at multiple hue angles (**Fig. 6**). ITP more closely follows the lines of predicted constant hue than Y′CbCr for the worst case measured by the maximum absolute hue deviation. The most notable improvement with hue linearity is the lack of large deviations in ITP as opposed to those found on the right of the constant hue Y′CbCr plot. **Table 1** showed the average and maximum absolute hue deviation of ITP and Y′CbCr, respectively.



▲**Figure 4. Iso-intensity performance.**



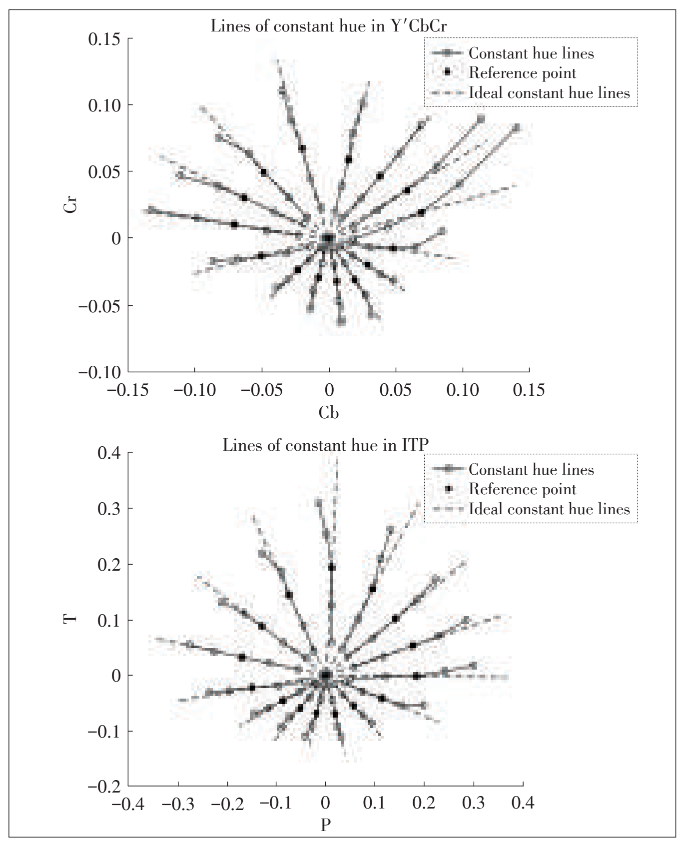
▲**Figure 5. Comparison of constant luminance performance of ITP and NCL Y′CbCr-PQ.**

2.2.4 Chroma Downsampling Property

Similar to Y′CbCr, ITP is also friendly to 4:2:0 chroma downsampling, which is the common chroma sampling format used in video compression. **Table 2** shows the difference in dB in objective metrics computed from a conversion only workflow for ITP and Y′CbCr-PQ. The details of those objective metrics are referred to in [12]. The MPEG CfE chroma down/up sampling filters are applied. The conversion flow is as follows: RGB 4:4:4 (12 or 16 bit depending on content) ->Y′CbCr-PQ 4:2:0 10 bit /ITP 4:2:0 10 bit -> RGB 4:4:4 (original bitdepth). ITP has overall higher PSNR in luminance channel (Y) and overall colour metrics (DE) than Y′CbCr NCL, and is suitable for compression in the 4:2:0 domain.

3 ITP Compression Performance

As well as having better baseband signal properties than the



▲**Figure 6. Constant hue.**

▼**Table 1. Absolute hue deviation of ITP and Y′CbCr**

	Absolute Hue Deviation (degrees)	
	Average	Maximum
ITP	2.34	7.79
Y′CbCr	2.95	16.6

▼Table 2. Objective metric differences for conversion-only (ITP 10bit – Y′CbCr-PQ 10bit)

Sequence	Diff tPSNR Y	Diff DEPSNR
FireEater	6.57	0.97
Tibul2	10.8	0.83
Market3	7.81	0.17
AutoWelding	8.31	0.17
BikeSparklers	5.18	0.04
ShowGirl2	4.9	0.15
MagicHour	2.54	0.05
WarmNight	6	0.06
BalloonFestival	7.36	0.09
Average (dB)	**6.61**	**0.28**

NCL Y′CbCr-PQ, ITP can compress well. To evaluate the compression performance of ITP, two studies have been conducted: 1) compare transform coding gain with KLT; 2) compare covariance of ITP with Y′CbCr. We formed a test set of 19 frames representing all the scenes from MPEG HDR/WCG AhG sequences, i.e., one representative frame from each scene.

Transform coding gain is one metric to measure compression performance. It is defined by the ratio of the arithmetic mean to the geometric mean of the variances of the variables in the new coordinates, properly scaled by the norms of the synthesis basis functions for nonunitary transforms [16]. The coding gain is usually measured in decibels, representing the reduction in quantization noise by quantizing in the transformed domain instead of the original domain [16]. The test shows that the coding gain of ITP is 12.42 dB, while the coding gain using optimal KLT is 13.16 dB.

Another important statistical indicator for compression is the covariance matrix of the signal for 3 channels. We computed the covariance matrix of the test set with BT. 2020 Y′CbCr-PQ and ITP, both in 10-bit 4:4:4 Standard Range.

The covariance of 3 channels for Y′CbCr-PQ 10bit case is shown in **Table 3**, and that for ITP 10bit case is shown in **Table 4**.

By comparing the above two covariance matrix, we found that the variance of P channel is about four times of Cb channel and the variance of T channel is about four times of Cr channel, respectively. The cross-variances of IP and IT are about twice that of YCb and YCr, respectively. The cross-variance of PT is about four times of CbCr. This indicates that if we reduce the signal of P/T by half, i.e., representing P/T with 9 bit, the covariance matrix should be close to Y′CbCr case. **Table 5** is the covariance matrix for the newly generated ITP signal. They are indeed very close to Y′CbCr case in terms of covariance.

The conversion only results for I 10bit and PT 9bit compared with Y′CbCr 10bit case is listed in **Table 6**. By comparing Table 6 with Table 2, the conversion-only benefit of ITP over Y′CbCr is reduced but is still retained for majority testing content. One exception is the sequence BalloonFestival featuring very saturated colours, suggesting 9 bit is not good enough to signal chroma components for this content.

The compression simulation was also performed to test the performance of ITP. ITP colour space is implemented in HDRTools 0.8.1 [17]. HM16.2 [18] is used for compression test. The test sequences and targeted bitrate is listed in **Table 7**. For I 10bit and TP 9bit case, we used the same fixed QP as in the Y′CbCr-PQ anchor case. The compression results showed similar bit rate as the anchor. The BD-rate calculated using the suggested metrics is shown in **Table 8**. This is a fair comparison with Y′CbCr because a fixed scalar is used for P and T. Alternatively, we can simply encode the signal with HEVC by setting luma bit depth to 10 and chroma bit depth to 9. This shows that for DE100, which is considered as a performance indicator for colour reproduction, ITP with static reshap-

▼Table 3. The covariance of 3 channels for Y′CbCr-PQ 10bit case

	Y	Cb	Cr
Y	2.8949	-0.1304	0.0766
Cb	-0.1304	0.0730	-0.0314
Cr	0.0766	-0.0314	0.0321

▼Table 4. The covariance of 3 channels for ITP 10bit case

	I	T	P
I	2.5430	-0.2146	0.2099
T	-0.2146	0.2658	-0.1344
P	0.2099	-0.1344	0.1912

▼Table 5. The covariance matrix for the newly generated ITP signal

	I	T	P
I	2.8653	-0.1233	0.1214
T	-0.1233	0.0783	-0.0396
P	0.1214	-0.0396	0.0564

▼Table 6. Objective metric differences for conversion-only (ITP I 10bit PT 9bit - Y′CbCr-PQ 10bit)

Sequence	Diff tPSNR Y	Diff DEPSNR
FireEater	5.27	0.73
Tibul2	9.51	0.52
Market3	6.72	0.02
AutoWelding	7.74	0.13
BikeSparklers	4.84	0.02
ShowGirl2	4.23	0.05
MagicHour	2.17	0.04
WarmNight	5.58	0.04
BalloonFestival	6.39	-0.22
Average (dB)	**5.83**	**0.15**

▼Table 7. HDR/WCG test sequences and target rate points (kbps)

Class	Seq	Sequence name	Rate 1	Rate 2	Rate 3	Rate 4
A	S00	FireEater2Clip4000r1	1922	1260	812	521
	S01	Tibul2Clip4000r1	6101	2503	970	403
	S02	Market3Clip4000r2	7913	4224	2311	1248
B	S03	AutoWeldingClip4000	3157	1383	778	454
	S04	BikeSparklersClip4000	6119	4085	2184	1261
C	S05	ShowGirl2TeaserClip4000	3316	1652	971	574
D	S06	StEM_MagicHour	3959	2205	1302	771
	S07	StEM_WarmNight	2441	1328	780	462
G	S08	BalloonFestival	6644	3767	2156	1276

▼Table 8. Compression results (BD rates) compared to Y′CbCr-10b for I10b TP9b

	X	Y	Z	XYZ	tOSNR-XYZ	DE100	MD100	PSNRL100
FireEaterClip4000r1	-25.0%	-11.4%	53.4%	2.0%	-3.3%	-23.5%	-19.5%	-11.1%
Market3Clip4000r2	-6.1%	-1.4%	-3.8%	-3.8%	-5.5%	-23.5%	-7.2%	-1.7%
Tibul2Clip4000r1	-21.9%	-13.5%	150.3%	5.4%	11.5%	-15.6%	-7.2%	-11.4%
AutoWelding	-10.6%	0.2%	13.0%	1.5%	1.8%	-19.0%	-20.3%	3.1%
BikeSparklers	-10.5%	-1.0%	4.9%	-1.5%	-3.3%	-21.2%	-16.8%	0.0%
ShowGirl2Teaser	-10.9%	-1.7%	-7.7%	-6.7%	-10.4%	-22.6%	-25.8%	-2.2%
StEM_MagicHour	-9.6%	-1.2%	-3.9%	-4.7%	-5.2%	-15.9%	-19.7%	-1.0%
StEM_WarmNight	-13.0%	-1.0%	6.4%	-0.8%	-1.7%	-22.1%	-28.2%	-0.5%
BalloonFestival	-7.8%	-2.2%	2.6%	-1.5%	-2.8%	-7.7%	-23.5%	-2.8%
Overall	**-12.8%**	**-3.7%**	**23.9%**	**-1.1%**	**-2.1%**	**-19.0%**	**-18.7%**	**-3.1%**

ing can gain 19% over Y′CbCr-PQ.

These findings suggest that ITP 10 bit signal contains more colour information than Y′CbCr-PQ 10 bit signal. Since the baseband signal has much better representation in colour, it gives compression much more flexibility for having a "better" signal to start with. Considering this aspect, a technology called adaptive reshaping is incorporated into ITP to adaptively adjust the quantization of luma and chroma components and maximize coding efficiency. The evidence is shown in the MPEG CfE ADI proposal [11] and CfE test results report [19], and MPEG Core Experiment CE2.1.1 results [20] where advanced reshaping is applied in ITP colour space. In all those tests, ITP has shown superior compression performance compared to the MPEG CfE anchor. **Table 9** list results in MPEG HDR/WCG CE2.1.1.

When compared on an HDR display, the ITP with advanced reshaping can significantly improve compression performance of the HEVC Main 10 Anchors. The colour patches/blotches are mitigated substantially in low to medium bitrate compression. Besides, it can also improve texture preservation. **Fig. 7** shows the snapshots taken during the side-by-side (SbS) viewing on the HDR reference display Pulsar, for the test sequences "Market3" (copyright @ Technicolour) in MPEG CfE ADI solution. The circled areas show the most significant improvements over the anchor. For example, at similar bitrates, the details on the wall and wood frames in Market3 are better preserved (Fig. 7).

▼Table 9. Compression results (BD rates) of MPEG HDR/WCG CE2.1.1

	X	Y	Z	XYZ	tOSNR-XYZ	DE100	MD100	PSNRL100
FireEaterClip4000r1	-11.8%	4.9%	19.2%	2.4%	-0.3%	-21.3%	-32.3%	-6.4%
Tibul2Clip4000r1	-8.7%	2.9%	11.6%	-0.7%	-4.8%	-22.1%	-16.0%	-5.3%
Market3Clip4000r2	12.4%	20.6%	-13.2%	3.6%	-12.1%	-70.5%	0.0%	-17.2%
AutoWelding	-15.4%	-0.8%	-13.6%	-10.6%	-10.9%	-48.0%	-21.8%	1.8%
BikeSparklers	-16.8%	-5.1%	-17.2%	-13.8%	-16.5%	-48.1%	-11.6%	-5.0%
ShowGirl2Teaser	4.9%	19.3%	-6.6%	4.7%	1.5%	-48.6%	0.0%	-5.4%
StEM_MagicHour	-8.2%	2.5%	-10.3%	-6.8%	-8.5%	-34.5%	-21.4%	1.3%
StEM_WarmNight	-6.0%	9.5%	-5.0%	-1.5%	-2.7%	-42.7%	-45.9%	2.0%
BalloonFestival	56.9%	86.9%	110.2%	88.5%	28.7%	-45.0%	-77.9%	-1.5%
Overall	**0.8%**	**15.6%**	**8.3%**	**7.3%**	**-2.8%**	**-42.3%**	**-25.2%**	**-4.0%**

▲Figure 7. Market3 (from Technicolor) coded at R3: (a) ADI (2305 kbps), (b) Anchor (2311 kbps).

4 Conclusions

In this paper, ITP 10 bit is shown to have better baseband properties than Y′CbCr-PQ 10 bit. The compression performance of ITP 10 bit is also justified with compression results both in MPEG HDR/WCG CfE and following Core Experiments. The other property of ITP also shows that it is a good fit for colour volume mapping too. ITP is shown to work well for full HDR and WCG video delivery pipeline. Therefore, it is desirable to endorse ITP as a new signal format for HDR/WCG signal.

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References

[1] *Parameter Values for the HDTV Standards for Production and International Programme Exchange*, ITU-R BT.709, 2015.

[2] *Reference Electro-Optical Transfer Function for Flat Panel Displays Used in HDTV Studio Production*, ITU-R BT.1886, 2011.
[3] H. Basse, W. Aylsworth, S. Stephens, *et al.*, "Proposed standardization of XYZ image," Doc. m30167, Vienna, Austria, Jul. 2013.
[4] *HEVC*, Recommendation ITU-T H.265, International Standard ISO/IEC 23008-2, 2013.
[5] Blu-ray Disc Association, "Ultra HD Blu-ray Video Parameters Liaison Information," Doc. m36740, Warsaw, Poland, Jun. 2015.
[6] D. Le Gall, A. Tourapis, M. Raulet, *et al.*, "High dynamic range with HEVC main10," JCTVC-U0045, Warsaw, Poland, Jun. 2015.
[7] *Parameter Values for Ultra-High Definition Television Systems for Production and International Programme Exchange*, ITU-R BT.2020, 2015.
[8] A. Luthra, E. Francois, and W. Husak, "Call for evidence (CfE) for HDR and WCG video coding," Doc. N15083, Geneva, Switzerland, Feb. 2015.
[9] *Electro-Optical Transfer Function for High Dynamic Range Reference Display*, Society of Motion Picture and Television Engineers ST 2084, 2014.
[10] *Electro-Mastering Display Colour Volume Metadata Supporting High Luminance and Wide Colour Gamut Images*, Society of Motion Picture and Television Engineers ST 2086, 2014.
[11] D. Baylon, Z. Gu, A. Luthra, *et al.*, "Response to call for evidence for HDR and WCG video coding: Arris, Dolby and InterDigital," Doc. m36264, Warsaw, Poland, Jul. 2015.
[12] A. Luthra, E. Francois, and W. Husak, "Call for Evidence (CfE) for HDR and WCG Video Coding," Doc. N15083, Geneva, Switzerland, Feb. 2015.
[13] G. M. Johnson, X. Song, E. D. Montag, and M. D. Fairchild. "Derivation of a colour space for image colour difference measurement," *Colour Research & Application*, vol. 35, no. 6, pp. 387–400, 2010.
[14] F. Ebner and M. D. Fairchild. "Development and testing of a colour space (IPT) with improved hue uniformity," in *Colour and Imaging Conference*, Scottsdale, USA, Nov. 1998, pp. 8–13.
[15] J. Froehlich, T. Kunkel, R. Atkins, *et al.*, "Encoding colour difference signals for high dynamic range and wide gamut imagery," in *Colour and Imaging Conference*, Darmstadt, Germany, Oct. 2015, pp. 240–247.
[16] H. Malvar, G. Sullivan, and S. Srinivasan, "Lifting-based reversible colour transformations for image compression", in Proc. SPIE 7073, Application of Digital Image Processing XXXI, San Diego, USA, 2008. doi: 10.1117/12.797091.
[17] MPEG SVN [Online]. Available: http://wg11.sc29.org/svn/repos/Explorations/XYZ/HDRTools/tags/0.8.1
[18] HEVC [Online]. Available: https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/tags/HM-16.2
[19] MPEG requirement, "Test Results of Call for Evidence (CfE) for HDR and WCG Video Coding", Doc. N15350, July 2015, Warsaw, Poland.
[20] D. Baylon, Z. Gu, A. Luthra, *et al.*, "CE2.1.1: single layer HDR-only solution based on m36264", Doc. m37070, Geneva, Switzerland, Oct. 2015.

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