Abstract—New emerging technologies in the field of multimedia, such as high dynamic range and wide color gamut, challenge the performance of existing image and video data processing algorithms, especially in terms of visual data compression and its faithful representation. High dynamic range and wide color gamut offer to capture and to represent a scene with extended amount of details in both, luminance and chrominance, respectively. This paper presents and evaluates possible solutions to cope with such extended amount of visual information while delivering a faithful representation of visual information. More particularly, two approaches proposing novel color space, a constant intensity color difference signal representation called ICtCp, and novel compression optimization algorithm, reshaper, are described and subjectively evaluated. The results of the conducted experiments show competitive performance of two proposed approaches, ICtCp and reshaper, allowing 10% bitrate reduction while preserving the perceived quality.

Index Terms—HDR, WCG, ICtCp, Y’CbCr, color space, compression, subjective evaluation, partial pair comparison.

1 INTRODUCTION

Recent fast technological progress in displays, data representation, and compression offers broader options in multimedia services leading to an increase of user expectations in terms of quality and experience. In general, users expect to receive the most accurate visual information enabling more realistic and immersive sensations. To address such expectations, an intensive research effort has been dedicated to High Dynamic Range (HDR) and Wide Color Gamut (WCG) imaging.

HDR offers to represent a detailed visual information with a large variation of luminance, from deep dark (0.005 cd/m², also referred to as nits) to very bright (10,000 cd/m²) values. Luminance range represented by HDR better corresponds to properties of Human Visual System (HVS) in perceiving and accommodating several orders of luminance magnitude. In practice, HDR technology allows to capture and represent simultaneously bright (highlights) and dark (shadows) scenes with high level of details in a way that a more realistic perception is induced.

An HDR visual information is usually captured with higher bit depth precision, which results in increased amount of data. Therefore, an efficient compression algorithm preserving high image quality and faithful image representation is needed. The Standard Dynamic Range (SDR) compression algorithms usually operate on visual data represented in YCbCr color space with color gamuts corresponding to ITU-R Recommendations BT.601 or BT.709. The extension of compression algorithms to cope effectively with an HDR and WCG visual information must consider SDR backward-compatibility constraints as well as efficiency of the signal compression. In addition, new compression solutions must have similar complexity level when compared to current standards.

In [23], the authors demonstrate an effective compression algorithm using color space optimization. More specifically, a de-correlation of luminance and chrominance information as well as chrominance re-scaling and re-mapping is performed prior to encoding. This echoes the capabilities of the evaluated approaches as the adaptive reshaper changes luma and chroma characteristics for better coding efficiency and the luminance channel of ICtCp is achromatic. An evaluation of proposed ICtCp color space in a framework of an HDR and WCG visual data compression was previously performed [20]. The reshaper theoretical performance is assessed in [21]. However, the above-mentioned analyses are restricted to the use of objective metrics only.

In this paper, subjective experiments evaluating the performance of ICtCp are presented and their results are analyzed and discussed in details. Furthermore, a reshaper, adjusting pixel intensity values to optimize compression algorithms, is also evaluated and its performance is analyzed. Our main aim is to assess the two following assertions: (1) ICtCp signals quality will be preferred, or equally perceived, over YCbCr signals. (2) Reshaped signals, enabling 10% of bitrate saving, will be perceived as having a similar quality as compressed signals using current algorithms.

The remainder of the paper is organized as follows. Background information is provided in section 2. The design of conducted subjective experiments is exposed in section 3. Results giving the overall performance of the ICtCp color space and the reshaper are described and analyzed in section 4. Finally, conclusions are drawn in section 5.
2 BACKGROUND

This section sets a context of our study while providing a detailed definition of HDR and WCG as well as a comprehensive description of all evaluation aspects.

2.1 HDR and WCG

HDR and WCG imaging allows to capture and represent wider color gamut containing a larger amount of reproducible colors, when compared to SDR. This fact allows to provide users with a more realistic sensation and a more accurate visual information.

In general, the HDR technology aims at a more realistic representation of visual information. It allows to better cope with the HVS ability to generally perceive about ten orders of magnitude of luminance [7] and to accommodate to about five orders of magnitude simultaneously [24]. The improvement of the reality sensation is mainly due to the more accurate rendering of nuances in colors and luminance present in a scene. For instance, the extension of the dynamic range permits having more accurate highlights and shadows. HDR new characteristics include higher peak luminance, lower minimum luminance, greater contrast range, and improved precision minimizing quantization errors that are beyond the capabilities of existing standards.

On the other hand, a color gamut is a subset of colors representing the proportion of the visible spectrum that a rendering and/or visualization system can reproduce. It is usually represented by a triangle in the CIE 1931 XYZ color space xy chromaticity diagram. WCGs, such as BT.2020 [11], are required to accurately represent visual information since they allow to render more colors than standard color gamuts, such as BT.709 [17]. Figure 1 shows the CIE 1931 XYZ color space xy chromaticity diagram and the representation of the BT.709 and BT.2020 color gamuts.

HDR and/or WCG representation of visual information requires more storage, when compared to SDR. Therefore, an efficient compression algorithm of HDR and WCG content is needed. Current standards for HDR image and video compression are JPEG 2000, JPEG XR, JPEG XT [1] and HEVC Format Range Extension (RExt) [18]. Nevertheless, the compression process is not the only solution to reduce the bitstream bandwidth and to improve HDR and WCG content distribution. Several solutions have been proposed and described within SMPTE [25], [26]. Among others, the BBC Hybrid Log-Gamma (HLG), the Dolby Vision® end-to-end service, and the Samsung solution for dynamic metadata have been proposed.

In the scope of this paper, we consider the improvements of data representation using either a new color space or a mapping function (reshaper) enabling bitrate saving.

2.2 Color Spaces

Usage of each particular color space leads to specific compression artifacts. For instance, significant color artifacts result from the use of Non-Constant Luminance (NCL) YCbCr representation as color impairments spread to luminance channel, where distortions are more noticeable. Using the Constant Luminance (CL) Y’CbCr representation, prevents above mentioned color artifacts, however, it requires more computation power due to higher complexity.

2.2.1 YCbCr color space

The International Telecommunication Union (ITU) standardized the YCbCr color space within the first version of the ITU-R BT.601 in 1982 [16]. YCbCr is composed of a NCL channel Y and the blue- and red-difference chroma components Cb and Cr, respectively. Several variants derives from YCbCr to transcend its limitations. A non linear filter, such as a gamma correction, can be applied to the luminance channel in order to reduce quantization errors perception. The resulting representation is commonly referred to as Y’CbCr. When nonlinear filtering is also applied to the chrominance components, the obtained color space is referred to as Y’Cb’Cr’ . The CL Y’CbCr (or Yc’CbcCrc) addresses the issue of the correlation between luma and chroma components.

The color space used in the conducted experiments is Y’CbCr. Its definition is provided in [13] and its gamut mapping equations are presented in [11], [17]. When considering HDR and WCG, the limitations of Y’CbCr representation can be listed as follows [14]:

- quantization distortions (bit depth limitations),
- chroma sub-sampling distortions due to perceptually uneven distribution of code words,
- color volume mapping distortions due to incorrectly predicted hue and luminance, and
- error propagation from chroma to luma channel.

2.2.2 ICtCp color space

Recently, Dolby Laboratories have proposed an ICtCp color space [13] addressing the limitations of Y’CbCr. ICtCp extends known IPT color space [6] by exploring higher dynamic range (up to 10000 cd.m⁻²) and larger color gamuts (e.g. BT. 2020) [20].

The process of ICtCp mimics the early stages of human color vision described hereinafter. The eye is composed by three photo receptors (cones). Each cones is particularly sensitive to long (L), medium (M), or short (S) wavelengths. The lighting adaptation process of the eye consists of a nonlinear signal response to reduce dynamic range. This nonlinear output goes through a color differencing process to extract important information and to separate the signal into three distinct components. This explains the following ICtCp conversion steps: (1) compute LMS response, (2) apply nonlinear encoding Perceptual Quantizer (PQ) transfer function, (3) apply color differencing equation (3x3 Matrix). The detailed process of ICtCp transform is described in [5].
and illustrated in Figure 2, where intensity (I) corresponds to nonlinear brightness of pixels, and yellow-blue Tritan (Ct) and red-green Protan (Cp) are the color channels. The characteristics of the ICtCp color space are exposed and demonstrated in [9], [14], [20] and summarized below.

- Achromatic channel I and isoluminance: mutual information of chroma and luma channels will result in severe discrepancies after compression. The decorrelation between luminance and chrominance prevents having such artifacts. In addition, the intensity channel I corresponds closely to the PQ luminance Y. Therefore, ICtCp is isoluminant.

- Hue linearity: a color space is hue linear when the hue remains constant as saturation or intensity are changed. ICtCp has straighter constant hues lines than Y’CbCr.

- Perceptually uniform colors: the MacAdam ellipses [22] are more circular in ICtCp color space when compared to Y’CbCr. Therefore, ICtCp is perceptually uniform, leading to efficient color sub-sampling.

- Quantization to limited bit-depth: experiments demonstrate that 10 bit ICtCp provides an approximately 1.5 bit color difference improvement over 10 bit Y’CbCr, and at the same time presents less color quantization error.

Moreover, ICtCp and Y’CbCr have similar complexity of conversion because they require the same sequence of operations. Overall, the above mentioned characteristics favor the exploitation of ICtCp color space to represent HDR and WCG content.

2.3 Transfer functions

The consistency of multimedia content playback, regardless of the exploited display or compression scheme, is very important for service providers. Transfer Functions (TFs) define the transformations needed from camera to display in order to insure the above mentioned consistency. This section aims at defining main types of TFs and describes in particular the PQ and the HLG TFs.

- An Opto-Electro Transfer Function (OETF) converts linear scene light into the video signal, typically within a camera.

- An Electro-Optical Transfer Function (EOTF) converts the video signal into the linear light output of the display.

- An Opto-Optical Transfer Function (OOTF) has the role of applying the ‘rendering intent’. OOTF are usually a concatenation of OETF, artistic adjustments, and EOTF.

2.3.1 PQ

The PQ was designed based on the model shown in Figure 3b, where the OOTF is considered to be embedded in the camera (or imposed in the production process). This system is then defined by its EOTF. The PQ EOTF has been split into two steps: a linearization equation followed by a level calibration equation. The linearization was constructed to align with human visual contrast sensitivities over a specific range of luminance values. PQ specification achieves a very wide range of brightness levels for a given bit depth using a non-linear transfer function that is finely tuned to match the human visual system.

2.3.2 HLG

The HLG was designed based on the model shown in Figure 3c, where the OOTF is considered to be on the display side. This system is then defined by its OETF. A comprehensive description and analysis of this system is presented in [3]. HLG specification offers a degree of compatibility with legacy displays more closely matching the previous established television transfer curves.
2.4 Adaptive reshaper

The purpose of the adaptive reshaper, closely described in [2], [8], is to modify the post-EOTF signal. The reshaper is also able to create SDR from HDR signal. This capability will not be investigated during our experiments.

PQ functions are designed for a reference display with dynamic range from 0 to 10,000 cd/m². However, due to current display limitations, the video dynamic range might be smaller. The reshaper is designed to solve the problem of the range mapping of the content. In addition, HDR and WCG lead to larger color volumes. Therefore, the reshaper addresses color and intensity compression efficiency.

The reshaper is modeled for luma as a piece-wise polynomial of the second order, with up to 8 pieces. For chroma components, a piece-wise linear model with up to 32 pieces, is used. The reshaper improves the coding efficiency of a signal as the above-mentioned parametric reshaping models implement the following two features: (1) adaptive codeword re-distribution based on pixel brightness and (2) signal re-quantization among luma and chroma components, which ultimately changes the bit rate allocation for the three components.

The overall process of the reshaper starts with the pre-processing of the signal and its content and intent analysis. The signal is then adjusted and the transform curve is derived. The curve is then modeled in the luma and chroma polynomials which are transmitted along with the signal. The signal is applied to an encoder and compressed by normal means. Upon decoding, the polynomials are used to create a Look Up Table (LUT) and the decoded pixels are modulated by the LUT. The result of the post-process LUT is a representation of the original input signal. A comprehensive description of the reshaper process is exposed in [21].

3 SUBJECTIVE ASSESSMENTS

In this section, visual quality subjective assessments comparing performance of two different aspects are presented. First, perceived quality of HDR video sequences represented in two color spaces, Y’CbCr and ICtCp, is evaluated. Then, the performance of reshaper in each investigated color space is assessed. This investigation is, to the best of authors knowledge, the first attempt to subjectively assess the performance of above mentioned algorithms. The goal of such evaluation is to determine whether the use of ICtCp color space and the integration of reshaper can be justified in future HDR compression standards.

As previously mentioned, the ICtCp color space is designed to overcome constraints of Y’CbCr, such as luminance and chrominance channels correlation, bit-depth restriction, hue non-linearity, etc. Moreover, the design of the ICtCp color space reflects the properties of the HVS. The objective quality benchmarks of ICtCp performance in terms of compression efficiency were presented in [20]. Nevertheless, to reliably compare the visual quality of proposed algorithms, a subjective assessments need to be performed. This allows to completely and comprehensively appraise the benefits of using ICtCp for HDR and WCG.

Another way of increasing compression efficiency in HDR and WCG imaging is to use a reshaper. In general, reshaper is a mapping function used to adjust the pixel intensity values in a way that optimizes compression. The objective quality benchmarks of the reshaper performance in terms of compression efficiency were presented in [21]. The metrics used during objective quality benchmarks of reshaper performance and ICtCp compression efficiency were DE100, L100, X, Y, Z PSNR and OSNR metrics. Our aim is to verify the efficiency of the reshaper in terms of bitrate saving while preserving the perceived visual quality.

3.1 Test Material

This section defines the dataset, naming conventions, coding conditions, and other characteristics of the test material used in subjective experiments.

Five 16bit full HD clips of about 10 seconds were selected for our experiments, see Figure 4. Three MPEG contents, namely Market3, BalloonFestival, and ShowGirl2, were used as well as additional contents, namely EBU_06_Start and Rugby. Additional contents were selected as they represent a sport event broadcasting use-case scenario. Detailed characteristics of each content are summarized in Table 1. It should be noted that the frame rate of BalloonFestival and ShowGirl2 contents was doubled in our experiments. The Dolby Vision™ end-to-end service [4], [25] was used during the process of content creation. The BT.2020 color gamut was used for the content creation and visualization. Additionally, the PQ TFs were used to prepare ICtCp color space representation of test material.

To easily represent all testing conditions corresponding to proposed compression techniques, we denote two anchors and six different proponents as follows:

- P00: Y’CbCr without reshaper
- P10: Y’CbCr with reshaper. Reshaped at 100% bitrate of P00.
- P11: Y’CbCr with reshaper. Reshaped at 90% bitrate of P00.
- P12: Y’CbCr with reshaper. Reshaped at 80% bitrate of P00.
- P20: ICtCp without reshaper.
- P31: ICtCp with reshaper. Reshaped at 100% bitrate of P20.
- P32: ICtCp with reshaper. Reshaped at 90% bitrate of P20.
- P33: ICtCp with reshaper. Reshaped at 80% bitrate of P20.

The P00 will be referred to as anchor, the rest will be referred to as proponents. P20 is referred to as a proponent or an anchor, when comparing color spaces or reshaper efficiency, respectively.
TABLE 1: Characteristics of test stimuli.

<table>
<thead>
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<th>sequence</th>
<th>frames</th>
<th>fps</th>
<th>br [kbps]</th>
<th>Y’CbCr w/o reshaper</th>
<th>Y’CbCr w/ reshaper</th>
<th>ICtCp w/o reshaper</th>
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<td>1514 1453</td>
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</table>

3.2 Test Equipment and Environment

Two 1080p 2000 nits Maui monitors by Dolby were used to render the test stimuli. The displays’ peak luminance was set at 1000 nits. The Dolby Vision™ was used for the visualization process. As recommended in [12], the viewing distance between displays and subjects was set to 1.6H. H corresponds to the height of the active display area of each device.

The test laboratory room fulfills the ITU recommendations for Laboratory assessment, such as having homogeneous mid-grey painted walls as well as controlled temperature and ambient lightning.

3.3 Test Methodology

The performed experiments followed a partial Side by Side (SbS) Pair Comparison (PC) methodology described in [19]. One paired comparison, referred to as a test comparison, is defined as a set of two test stimuli. Each of the two Maui monitors, positioned SbS, renders one test stimuli of a test comparison, in a synchronous manner. Test comparisons were repeated twice in order to better cope with small differences between the test stimuli as well as their short duration. The position of test stimuli (left or right) as well as the order of test stimuli were randomized.

The subjects were asked to provide their quality preference assessment stating whether the stimuli on the right or on the left monitor was perceived with better quality taking into account the compression artifacts as well as a color fidelity. Ternary categorical scale (left, right, same) was used to acquire subjective scores.

Partial PC was used to reduce the amount of test comparisons. Proponents were compared to anchors at the corresponding bitrate only, leading to an overall amount of test comparisons of 200. More specifically, to evaluate the performance of color spaces, only pair comparisons between anchor P00 and ICtCp proponents P20, P30, P31, and P32 at corresponding bitrates were appraised. This leads to 80 test comparisons, i.e. 5 contents encoded with 4 bitrates using 4 proponents to be compared to an anchor. The 120 remaining test comparisons were performed to evaluate the efficiency of a reshaper and used paired comparisons between P00 and P1x, as well as between P20 and P3x (x = 1,2,3). This gives 5 contents encoded with 4 bitrates using 6 proponents to be compared to anchors.

In line with [15], viewing sessions were designed to last 20 minutes or less to avoid subjects fatigue and to prevent lack of concentration. Therefore, the entire test was divided into six test sessions. The sessions SA and SB were dedicated to the assessment of the proponents P20, P30, P31 and P32 in comparison to P00, where a comparison between Y’CbCr and ICtCp color spaces was performed. The four remaining test sessions addressed the reshaper efficiency assessment. More particularly, sessions SC and SD evaluated comparisons between P00 and P10, P11 and P12, whereas sessions SE and SF evaluated the differences between P20

Table 2: Subject panel’s characteristics of test sessions

<table>
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<tr>
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<th>SA-SB</th>
<th>SC-SD</th>
<th>SE-SF</th>
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<td>16</td>
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<td>Number of females</td>
<td>5</td>
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<td>10</td>
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<tr>
<td>Average age</td>
<td>22.35</td>
<td>21.91</td>
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</tr>
<tr>
<td>Standard deviation of age</td>
<td>3.39</td>
<td>3.12</td>
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Figure 5: Preference and tie probabilities of individual pairs. Y’CbCr anchor P00 is compared to ICtCp proponents. The green dashed lines split the distribution graphs in thirds, whereas the red dashed line delineates the halves.

Figure 6: Preference probability matrix for each bitrate and for each investigated condition proponent vs. anchor.

Information about subjects used in experiments are provided in Table 2. Overall, 20 scores per stimuli were gathered for sessions SA and SB, 22 scores per stimuli for sessions SC and SD, and 26 for sessions SE and SF. The proportion of men compared to women is about two thirds. The subjects were mostly students.

4 RESULTS & ANALYSIS

After collecting the preference ratings from the subjects, statistical tools were applied to analyze results. A first approach to analyze a set of pair comparisons is to compute the distribution of the votes for different categories (left, same, right) and normalizing them by number of subjects. This can be done individually for each or jointly over all contents. For each pair comparison, the normalized distributions indicate the proportion of quality-preference (left and right) as well as the proportion of non-preference or indistinguishable-difference (same). For a more detailed analysis of individual test conditions and their performance with respect to each other, one can construct a preference matrix from the individual pair comparisons by discarding the ties. Below, we assume equal distribution of ties between two remaining categories (left and right). It provides the preference probabilities of a test condition A versus another test condition B along the rows. Combining the results all together, we can successively reach a conclusion regarding the comparison between Y’CbCr and ICtCp color spaces as well as regarding the efficiency of adding a reshaper.

Y’CbCr vs ICtCp Comparison

In this subsection, we consider the results of sessions SA and SB dedicated to comparison of Y’CbCr and ICtCp color.
Figure 5 presents the resulting preference and tie probabilities of the proponents versus the anchor. One of the proponents P20, P30, P31, and P32 (condition A) is compared to anchor P00 (condition B). The observed results demonstrate no clear preference of the proponents over the anchor. However, some trends are noticeable. First, the overall impression provided by Figure 5f is that the perceptual difference between the two color spaces is negligible as subjects mainly rated them as same. Then, there is an evident content dependency in our results. Whereas the Y’CbCr is preferred considering the content C3, ICtCp is preferred considering content C2. Moreover, the results for the three remaining contents demonstrate the tendency that Y’CbCr is preferred at higher bitrates, whereas ICtCp is preferred at lower bitrates. This observation is especially valid for P20 and P30 proponents.

Figure 6 depicts the average probability to prefer a proponent matrix comparing both color spaces for all bitrates. There is a distinction in the results when considering the two highest bitrates or when considering the two lowest bitrates. In the former case, the Y’CbCr is preferred whereas ICtCp is preferred in the second. This fact supports previous observations. The P00 anchor slightly outperforms all proponents except P30 at bitrate R2. P30 is preferred over P00 for all bitrates. All the proponents using the reshaper present better probabilities than P20.

The overall trend is still a lack of preference of a color space over the other. However, the proponents using a reshaper allow bandwidth-saving while preserving or even improving the perceived quality.

Reshaper Comparison
This subsection presents and analyses the results of the remaining sessions dedicated to the assessment of the reshaper efficiency. Figure 7 presents the resulting preference and tie probabilities.

Overall, there is no proponent clearly out-performing the anchors as the distribution of votes among the three choices is almost equal.

Figure 8 depicts the average preference of proponents probability matrix for all bitrates and test comparisons related to an analysis of the reshaper efficiency. The results of bitrate R3 differ from the rest as P10 and P30 moderately.
out-perform their respective anchors while the authors’ preference probabilities exceed the other proponents. In the rest of the results, one can observe the efficiency of P10 and P30 for the two lower bitrates; P11 and P31 performs very well for all bitrates (except for R3, see comment above); P12 and, to a lesser extent, P32 present the poorest performance, when compared to the results of other proponents of their respective color space. Overall, the probability to prefer a reshaped proponent over its anchor are highest for ICtCp than for Y’CbCr.

In general, a reshaped signal will have an equal or an improved perceived quality compared to a non reshaped signal. The 90% reshaper is efficient at all bitrates. This result is engaging as this proponent provides at least the same perceived quality while saving 10% of bitrate. However, a reshaper achieving 20% of bitrate-saving does not maintain a suitable quality of signal. Reshaper’s efficiency is higher for ICtCp than Y’CbCr proponents.

5 Conclusion

The aim of the presented experiments was to evaluate the performance of ICtCp in comparison to Y’CbCr color space. The ICtCp proposes an achromatic luminance channel I and ensures hue linearity and perceptual uniformity. Moreover, a reshaper, capable of adjusting pixel intensity values to optimize compression, is evaluated for both color spaces. A partial pair comparison, side-by-side, with repetition methodology was used to conduct the experiments. More than 20 scores per stimuli were gathered for data processing.

Statistical analyses of the results show that in overall, there is no color space clearly preferred over the other. ICtCp signals have lesser perceived quality than Y’CbCr signals at high bitrates whereas they are slightly preferred at low bitrates. Combination of ICtCp and reshaper presents equal or increased perceptual quality, even though it allow bitrate-saving. Regarding reshaper efficiency, similar quality is perceived with and without it. Reshaped signals saving 10% of bitrate are noticeably preferred over non-reshaped signals, for all bitrate, for both color spaces. Finally, reducing the bitrate by 20% while preserving the perceived quality is an overestimation of reshapers’ capability to improve compression efficiency.

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