A Color Gamut Mapping Scheme for Backward Compatible UHD Video Distribution

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***Abstract*— The new Ultra High Definition (UHD) standard digital imagery can represent much more color information than High Definition (HD) and Standard Definition (SD). Currently most manufactured displays support UHD colors while UHD is being deployed for content production. However not all service providers have updated their pipeline thoroughly. Thus, the end-user that buys a UHD display would not be able to benefit from the wider UHD color range. In this paper, we propose an invertible gamut mapping from UHD colors to HD colors so that UHD displays can reconstruct UHD colors, while HD displays are addressed directly using legacy video delivery pipeline. The proposed color mapping scheme allows the mapped signal to be converted back to the original signal with minimal perceptual error so that the viewers' quality of experience (QoE) is preserved. Our method includes a parameter that adjusts the trade-off between the quality of the HD content and that of the UHD content. Our experiment results provide a guideline on how to strike a balance between color errors in the mapped signal and the retrieved one.**

Keywords—Gamut Mapping, Wide Color Gamut, Ultra High Definition, Video Processing, Color Processing, Quality of Experience

I. INTRODUCTION

The new Ultra High Definition (UHD) standard digital imagery can represent much more color information than High Definition (HD) and Standard Definition (SD) [1] [2]. While UHD TVs and UHD content are becoming widely available, the HD and SD TVs and content are still dominant in consumer market. Also, not all the service providers have updated their pipeline thoroughly. Thus, an end-user with a UHD display would not be able to benefit from UHD content wide color range, since the pipeline can only transmit HD/SD colors.

It is essential for service providers and broadcasters to ensure the quality of service (QoS) for their customers regardless of their display technology. In the distribution pipeline, the color gamut of the content needs to match that of the display so that content is interpreted and reproduced properly. If the color gamut of the content is the same as that of the display, the signal can be viewed directly without any further processing. However, the challenges arise when the content has a color gamut different from the one the display is capable of showing. One possibility is that the display's gamut is a subset of the content color gamut. In this case the source color gamut needs to be compressed into the smaller destination gamut. Fig. 1 plots on the CIE 1931 xy chromaticity diagram [3], the BT.709 gamut [1], the color gamut supported by conventional HD and SDR displays, compared to BT.2020 [2] gamut, the supported gamut by the new UHD and/or HDR displays. If the content is of BT.2020 gamut and the display is of BT.709 gamut, gamut compression should be applied on the content gamut. Another possibility is that the content gamut is smaller than that of what the display is capable of reproducing. In this case, if no information of the source gamut is present at the viewers' side, the content is viewed directly. However, if source gamut is known at the viewers' side (through metadata sent with the bitstream), gamut expansion can be applied to the content so that the viewers are benefited from the larger gamut display capabilities [4].

Fig. 2 (a) depicts the commonly used pipeline for 8-bit HD/SD content delivery that utilizes H.264/AVC [5] video coding standard. To support both HD and UHD, one solution is to update the existing pipeline with the recent video compression standard, High Efficiency Video Coding (HEVC) [6] [7], and replace all the existing set-top boxes (STB) with the new ones that have HEVC decoder and gamut mapping

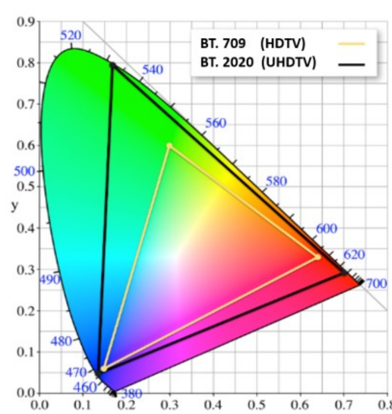

Fig. 1. CIE 1931 xy chromaticity diagram with the BT. 709 and BT. 2020 color gamut

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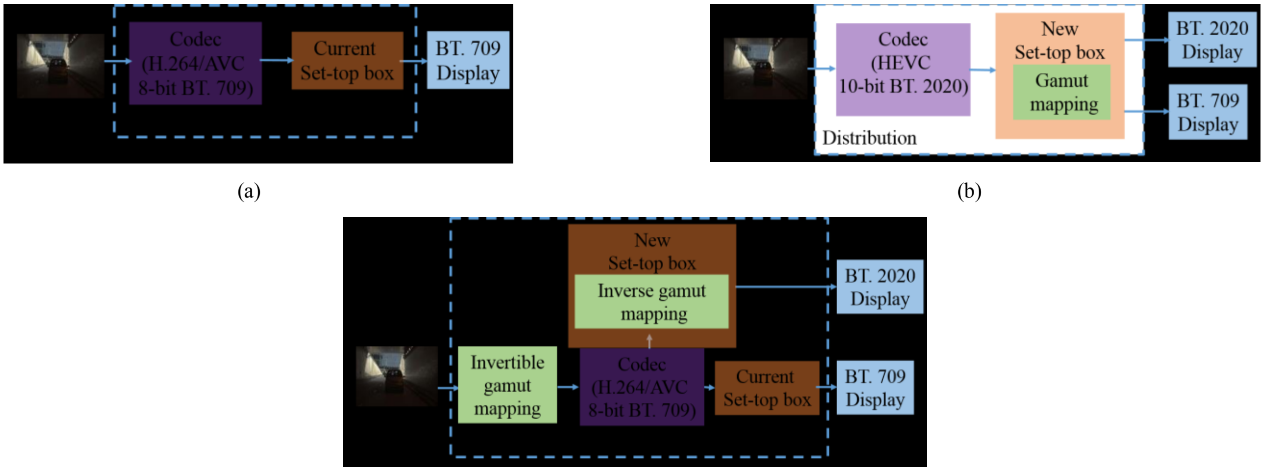

(a) (b) (c)

Fig. 2. (a) Current HD/SD distribution pipeline with 8-bit BT. 709 support, (b) future distribution pipeline with 10-bit BT. 2020 support, and (c) invertible gamut mapping compatible with the current distribution pipeline

functionality, as shown in Fig. 2(b). That imposes on the broadcasters an update on their distribution pipeline, which is quite costly and time consuming. The other alternative, during the transition phase from HD to UHD, is to preprocess the UHD content using an invertible gamut mapping scheme that compresses the BT.2020 gamut of the UHD content to BT.709 gamut and use the existing distribution pipeline to support customers with HD displays. For subscribers to UHD services, however, new STBs with gamut expansion capability are provided to retrieve the original colors of the source gamut (See Fig. 2 (c)). While this solution is quite cost-effective, the end users' quality of experience (QoE) relies on the performance of the gamut mapping scheme. An effective gamut mapping, would preserve the perceptual characteristics of the mapped signal such as lightness, hue and chroma through an adaptation process [8], and thus the viewed signal will have the same contrast and the same overall perceptual attributes [9].

In this paper we propose an invertible method for color gamut mapping from BT.2020 to BT.709 with minimal perceptual error. This method involves compressing the source gamut into the destination gamut and then expanding it to the original one using a scaling factor. The scaling factor adjusts the trade-off between the perceptual quality of mapped HD signal and that of the retrieved UHD signal to ensure the same QoE for all the viewers regardless of their devices' color gamut.

The rest of this paper is organized as follows. Section II provides background information on existing gamut mapping techniques. Section III describes the proposed method. Section IV discusses the results of the proposed method and lastly, conclusions are drawn in Section V.

II. Background

Gamut mapping is the process of color adaptation, usually from a larger source gamut to a smaller destination gamut [10]. In general, color gamut mapping can be categorized into two methods, point-wise and spatial. The former does not take into account any spatial information regarding the color pixels. Therefore, a source color will always be mapped to the same destination color, regardless of its position in the image. The latter technique, on the other hand, does take into account information of neighboring pixels. Using this technique one source color will be mapped to a different destination color depending on the colors of its neighboring pixels [11].

The point-wise technique also can be categorized into two methods, namely clipping and compression. Clipping involves mapping out-of-gamut colors using a projection line to the border of the smaller gamut without changing the inside-gamut colors. The compression method involves not only changing the out-of-gamut colors but also the colors inside the destination gamut so that color accuracy is maintained.

The clipping and compression methods map each out-of-gamut color to a color on the gamut border and an inside-gamut color, respectively (See Fig. 3). Which color on the border or inside the gamut will be the mapped color is determined through projection techniques. There are two projection methods, namely the Closest and Towards White Point (TWP).

TWP projects out-of-gamut colors to the line that connects

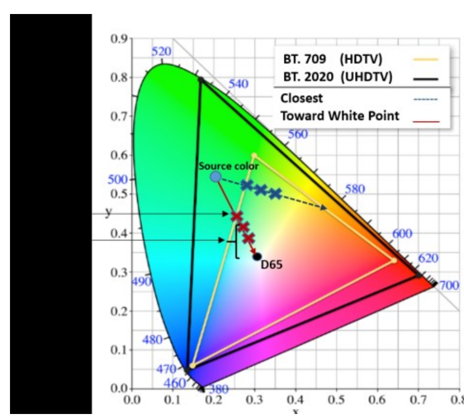

Fig. 3. Depiction of both gamut mapping methods of clipping and compression with both Towards White Point and Closest projection methods

the source color value to the white point (see Fig. 3, solid red line). If clipping is used, the color will be mapped to the intersection of this line and the gamut border. The Closest projection method maps out-of-gamut colors to a line that yields the minimum Euclidean distance between the source and mapped color value (see Fig. 3, dotted line). Again, if clipping is used, the intersection of this line and the gamut border will be the mapped color. In cases where the compression method is used, the destination color can be any point of the corresponding projection line, which lies inside the gamut. These points are shown in Fig. 3.

One application scenario in which clipping methods can be useful is depicted in Fig. 2 (b) where the gamut mapping process is performed at the viewers' side inside a set-top box or a TV display. To perform gamut mapping in the transmission pipelines as shown in Fig. 2 (b), one can choose a projection technique. The color space in which the mapping is performed is also determinative of the perceptual color error of the mapped signal. In [12], TWP and the closest projection techniques are evaluated in terms of the resulted color error, using different color spaces to perform the gamut mapping. The results of this study show that among the tested color spaces and projection techniques, the combination of the CIELAB color space [13] and Toward White Point (TWP) projection technique results in the least average error. In [14] a Look-up Table (LUT) is proposed, which includes the best combination of color space and projection methods for each color.

Fig. 2 (c) shows a scenario in which gamut mapping should be invertible. Since set-top boxes and TV displays may not be updated in a near future to support gamut mapping, broadcasters may need to send a mapped signal to viewers and let the ones with displays supporting a larger gamut retrieve the original gamut through an invertible gamut mapping process. In this case, clipping cannot be an appropriate method, as a subset the out-of-gamut colors has been mapped to a single color thus making inversion inaccurate. Compression, however, can be an appropriate mapping technique due to its many-to-many mapping relationship. During inversion, more colors of the original source gamut can be recovered with unnoticeable perceptual error [15].

By using compression for invertible gamut mapping, during inversion the colors that were inside the smaller gamut before mapping, will be re-mapped to the outside of the smaller gamut and inside the larger gamut. Therefore, color errors will be inevitably introduced for the inside-gamut colors. In our proposed method that is explained in details below, we try to strike a balance for the trade-off between the inside and outside-gamut color errors.

III. Proposed Method

In this work, we propose a method for point-wise gamut mapping from BT.2020 to BT.709 based on the compression projection technique. To indicate how far we compress the larger source gamut into the smaller destination gamut we introduce a scaling factor, α. We test different values of α ($\alpha \in [0,1]$) to find the one that yields the least color error, both when the color is mapped to the smaller gamut and when it is inverse-mapped to the original gamut. Fig. 4 shows an example of a gamut area inside BT.709 resulting from a specific scaling factor value.

Our method employs CIE ΔE2000 [16] as the color error metric to evaluate the perceptual error in the mapped colors. For the CIE ΔE2000 metric to work, it should be calculated on a perceptually uniform space, where the color components are de-correlated. For this reason, we use the CIE LC*h* color space to perform the gamut mapping process. This color space is commonly used in traditional gamut mapping [10].

The proposed gamut mapping scheme is based on the TWP projection method described in [12], as it is shown that it results in less color error compared to closest method, on average. In addition, by using TWP the direction in color space at which the pixels have been mapped is known.

The proposed method only needs the scaling factor to be sent as the metadata, as long as we assume that the source color gamut and color space in which the mapping was performed are known.

The proposed method application is shown in Fig. 2 (c). As it can be seen, there are two steps involved in the gamut mapping process. First the BT. 2020 gamut, which is the gamut of the original video content, needs to be reduced to BT.709 before encoding. After decoding the video, the BT.709 gamut needs to be expanded to BT.2020 (inverse

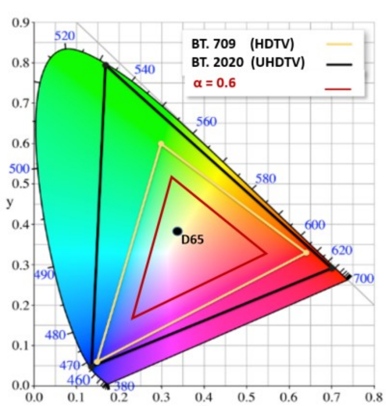

Fig. 4. Effect of scaling factor, α, on the size of the inner gamut inside BT. 709 gamut

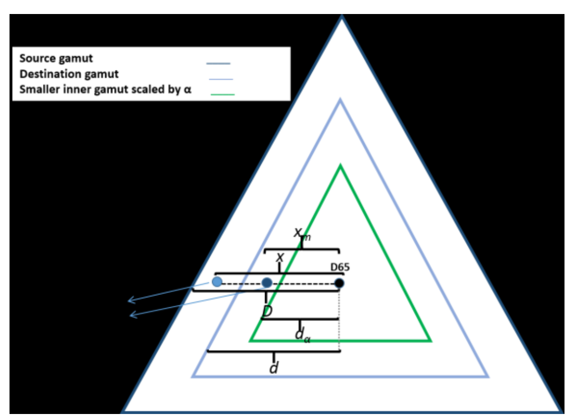

Fig. 5. Relationship between larger (BT. 2020), smaller (BT. 709) and inner gamut (scaled by α) distances and the original and mapped color

gamut mapping) so that the signal can be displayed on a device that supports BT.2020.

Therefore, the proposed mapping process will result in two mapped signals; one that is compressed into BT.709 gamut and the other one that is compressed into BT.709 and then expanded back into BT.2020 gamut. These two are explained in more details below.

A. Gamut Compression

If the out-of-gamut color has a distance x from the white point, then the distance of the corresponding mapped color from the white point, x_m, is:

$$x_m = \begin{cases} x - (D - d) \times (\frac{x - d_\alpha}{D - d_\alpha}), & x > d_\alpha \\ x & , otherwise \end{cases} \quad (1)$$

, where D is the distance from the gamut border of BT.2020 to the white point, d is the distance from the gamut border of BT.709 to the white point and d_α is the distance from the gamut border of the new smaller gamut inside BT.709 to the white point (which is essentially $\alpha \times d$). Fig. 5 shows these parameters and their relationship. Please note that for simplicity, we just show an approximation of the three gamuts in Fig. 5.

B. Gamut Expansion

If the scaling factor of α is known at the viewers' side, the mapped colors can be expanded back to the source color gamut. The distance of the mapped color inside the destination gamut from the retrieved color inside the source gamut will be:

$$x = \begin{cases} x_m + (D - d) \times (\frac{x_m - d_\alpha}{d - d_\alpha}), & x_m > d_\alpha \\ x_m & , otherwise \end{cases} \quad (2)$$

This process will cause some of the inside-gamut colors of the BT.709 to also go through the inverse mapping process. This will inevitably generate some color distortions for these colors.

C. Bit-depth Considerations

In our proposed method, we represent the BT.2020 gamut with 10 bits, while we use 8 bits for representing the colors of the BT.709 gamut [17]. Therefore, by going from BT.2020 to BT.709 and then going back to the BT.2020 color gamut using our method, some colors will be lost through quantization.

IV. Results and Discussions

We use the CIE ΔE2000 metric to evaluate the performance of the proposed color mapping scheme. Table 1 presents the results of mapping BT.2020 gamut colors into BT.709 gamut using different α values between 0 and 1. Note that α = 1 results in a gamut essentially the same as BT.709. Hence, we only report up to value of 1. It can be observed from the results in Table I that the smaller the α value is, the larger is the mean error and the percentage of colors with error larger than one. Please note that an error less than 1 in terms of CIE ΔE2000 means that both colors are perceptually similar, while errors equal and larger than 1 indicate that we can see the difference between the colors.

It is expected from the results of Table I that as α gets closer to one, the error decreases and becomes closer to zero since the inner gamut gets closer to BT.709 gamut. However, due to the quantization error resulting from going from 10-bit to 8-bit content, the average error and the percentage of pixels with error more than 1 in terms of CIE ΔE2000 is still relatively large.

Table II presents the results of the invertible gamut mapping when mapped back to the original BT.2020 gamut. From these results it can be seen that the parameter α has a large impact on the perceptual color error. If α is small, it means that more out-of-gamut colors can be mapped into inside colors, while others are mapped to gamut border. Therefore, inside-mapped colors can be retrieved back to the outside colors again with lower error.

For instance, in the case of α = 0.1, 95.6% of the colors are mapped inside and hence the mean error is low with most of the colors having no perceptible error (CIE ΔE2000 >1). However, even in the case of α being as small as 0.1, there is still the quantization error, as the 10-bit colors are mapped to 8-bits and then retrieved to 10-bit colors again during the inverse process.

By comparing the results of Table I and Table II, it seems that there is no general value of α that results in the least color error for mapping BT.2020 to BT.709 and BT.709 to BT.2020. However, to find an appropriate α, for each video content, an analysis on their color distribution can be performed. If most of the colors of the content lay on the outside of the BT.709 gamut, then one can choose a smaller α, or in other words a larger distance between the BT. 09 gamut and the new inner gamut. Similarly, if most of the colors of the content lay inside the gamut of BT.709, then a larger α may be a more appropriate choice so that colors inside the BT.709 gamut are preserved more. This will be part of our future work on this topic.

V. Conclusions

In this paper we proposed an invertible method for color gamut mapping from BT.2020 to BT.709 and then back to BT.2020. One specific application of this method is transmission of UHD and/or HDR video content to viewers with both BT.709 and BT.2020 capable displays. A scaling factor is introduced that controls the mapping process. The lower the scaling factor, the more is the distance of an original outside-gamut color to the inside-gamut mapped color. Prior knowledge of the distribution of the content pixels would lead to an "optimum" selection of the scaling factor. If most of the colors lay outside of the BT.709 gamut, then a smaller scaling factor can be chosen. Otherwise, a larger scaling factor is more appropriate.

TABLE I. RESULTS OF GAMUT MAPPING FROM BT.2020 TO BT.709 IN TERMS OF THE CIE ΔE2000 METRIC.

Color Space	α	Mean Error	% error > 1	% of mapped pixel
*LC*h**	0.1	5.01	91.4	95.6
	0.2	4.80	83.4	89.7
	0.3	4.69	75.4	82.7
	0.4	4.64	67.6	75.3
	0.5	4.63	60.1	67.6
	0.6	4.66	52.9	59.9
	0.7	4.74	46.0	52.2
	0.8	4.86	39.3	44.6
	0.9	5.05	32.9	37.1

TABLE II. RESULTS OF INVERSE GAMUT MAPPING FROM THE RESULTED BT.709 TO BT.2020 IN TERMS OF THE CIE ΔE2000 METRIC.

Color Space	α	Mean Error	% error > 1	% of mapped pixel
*LC*h**	0.1	0.08	0.194	95.6
	0.2	0.08	0.202	89.7
	0.3	0.08	0.240	82.7
	0.4	0.08	0.265	75.3
	0.5	0.08	0.285	67.6
	0.6	0.08	0.323	59.9
	0.7	0.09	0.383	52.2
	0.8	0.10	0.663	44.6
	0.9	0.14	0.773	37.1

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