New Color Encoding Method and RGB Primaries for Ultrahigh-Definition Television (UHDTV)

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Abstract

The present study introduces a new RGB-primary set and a new color encoding method suitable for Ultrahigh-Definition TV (UHDTV) that is considered as one of next-generation TV systems. The new RGB primaries for UHDTV were proposed by taking into account real surface colors and the colorimetric characteristics of flat panel displays such as LCD and AMOLED. The new color encoding method was developed to enable luminance and chrominance information to be almost accurately separated in the attempt to solve the drawback that Recommendation ITU-R BT.709 has. The new luma and color-difference signals generated by the newly derived encoding scheme were demonstrated to have insignificant crosstalk. It was also proved that this fact could contribute to improving image quality after subsampling color-difference components and to increasing efficiency in the image compression process.

Introduction

Viewers expect next-generation TV systems beyond HDTV that will be able to offer more realistic sensation, higher transparency to the real world, and more accurate visual information compared with HDTV systems. Ultrahigh-Definition Television (UHDTV) is considered to be one of such TV systems. NHK started research on UHDTV from the mid 1990s and developed first UHDTV prototype system in 2002 [1]. UHDTV broadcasting services are expected to be commenced from 2020 – 2025. One of key development factors for UHDTV is the sense of presence that viewers are aware of being there. The sensation of presence was evaluated and found to increase from the visual angle of 20 degrees and to reach a maximum at 80 to 120 degrees [2]. To realize this requirement, large flat panel displays, currently using LCD technology, with higher spatial resolution (e.g., 3840×2160 and 7680×4320) than 1920×1080 for HDTV are under development.

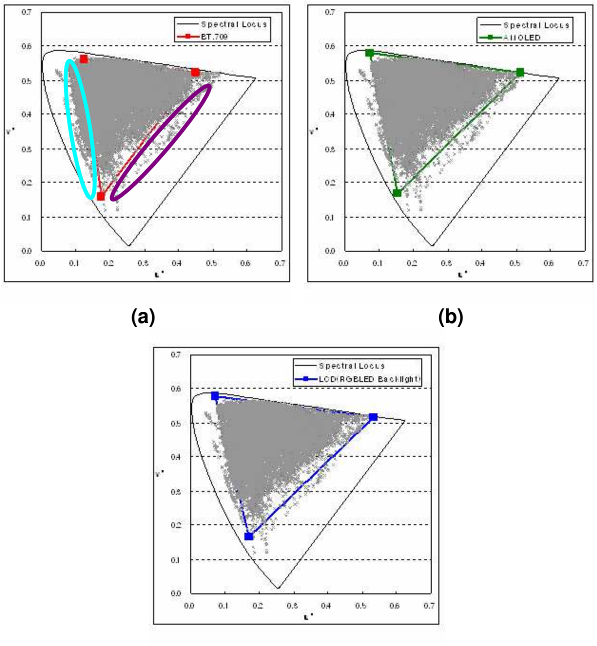
Recommendation ITU-R BT.709 is being widely used for producing and internationally exchanging HDTV broadcasting programs [3]. The reference RGB primaries defined in that recommendation were determined on the basis of colorimetric characteristics of a CRT. In the production of HDTV programs, all the colors captured using video cameras are firstly defined within the gamut formed from the CRT-centric reference RGB-primaries. These colors are then transformed into two types of video signal (Y' and $C'_BC'_R$) called luma and color-difference components that represent luminance and chrominance information respectively. Only the $C'_BC'_R$ signals are generally subsampled in the format of 4:2:2 for HDTV program production stages and in the format of 4:2:0 for emission of the produced programs to end-users. A compression tool such as MPEG 2 is applied to the 4:2:0 subsampled images in order to transmit HDTV programs within 6 MHz bandwidth [4]. There is a known drawback – crosstalk – in the $Y'C'_BC'_R$ video signals [5, 6]: luma (Y') signal contains chrominance information and vice versa. Due to the crosstalk problem, luminance information can also be manipulated by subsampling color-difference components of $C'_BC'_R$. As a result, the quality of decoded images after the subsampling process is degraded especially in the reproduction of sharp edge areas and the region including details or fine texture, resulting in blurred image appearance. The preservation of luminance information is very important for the accurate presentation of the areas containing sharp edges and details due to the nature of human eyes that perceive more sensitively spatial changes in the luminance dimension than those in the chrominance dimension.

The present study therefore attempted to develop a new encoding scheme that can enable luminance and chrominance information to be almost completely separated. Once UHDTV programs are produced and transmitted using the video signals created through such a new encoding scheme will have insignificant crosstalk, leading to improved image quality than the case using the conventional video signals of $Y'C'_BC'_R$. Additionally, a new RGB-primary set was also proposed for UHDTV systems. Because the flat panel displays (FPD) such as LCD and AMOLED will very likely be used to present UHDTV programs and commonly have wider gamut than the conventional CRT. This fact requires the need to establish a new RGB-primary set suitable for UHDTV. The final goal of the current study is to contribute to establishing a new recommendation defining image format for UHDTV systems.

A new RGB-primary set for UHDTV

Comparison of the gamut of ITU-R BT.709 with the real surface colors

There are two available data sets that can be a representative of real surface colors: Pointer's colors in 1980 and Standard Object Color Spectra (SOCS) database in 2003 [7, 8]. Pointer's data provided in the form of CIELAB $L^* C^*_{ab} h^*_{ab}$ values under the CIE C/2° condition were converted to those under CIE D65/2° condition using the CAT02 chromatic adaptation transformation embedded in the CIECAM02 color appearance model [9]. The tristimulus values, XYZ, were computed from the reflectance and the transmittance data of the SOCS set under the CIE D65/2° condition. Figure 1(a) shows whether the CRT centric gamut of ITU-R BT.709 encompasses the real surface colors of Pointer and SOCS database in the CIE u′v′ diagram. An AMOLED and an LCD equipped with a RGBLED backlight (or White-LED) will be a major type of large-size display devices capable of reproducing UHDTV contents. Figures 1(b) and 1(c) thus compare the real surface colors with the reproducible color ranges of the AMOLED and the LCD equipped with RGBLED in the u′v′ diagram [10]. The real surface colors of Pointer and SOCS database are indicated by gray cross in Figure 1.



(a) (b)

(c)

Figure 1. *Comparison of the real surface colors (×) in the CIE u'v' diagram with (a) the gamut of Recommendation ITU-R BT.709, and the reproducible color ranges (b) by the AMOLED and (c) by the LCD equipped with a RGBLED backlight.*

The gamut of ITU-R BT.709 in Figure 1(a) is seen not to cover all the real surface colors especially in green-blue and red-blue regions. Figures 1(b) and 1(c) demonstrate that the gamut of the AMOLED and the LCD can encompass majority of the real surface colors. The new RGB primaries were therefore derived by encompassing efficiently most of the real-world surface colors and by taking into account the characteristics of flat panel displays such as AMOLED and LCD on which UHDTV programs would be presented. The latter factor was reflected in the determination of new RGB primaries by attempting to place them to be close to the constant hue lines of the RGB primaries of the AMOLED and the LCD. In fact, the RGB primaries defined in ITU-R BT.709 were established by considering the colorimetric characteristics of a CRT.

Determination of new RGB primaries

Figure 2 shows newly derived RGB primaries for UHDTV in the CIE u′v′ diagram. Table 1 introduces their chromaticity coordinates. The constant hue lines of the RGB primaries of the AMOLED and the LCD are also seen. Individual data points (open or filled squares) on each of the constant hue lines have different chroma values but identical hue. The gray points in Figure 2 represent the real surface colors composed of Pointer and SOCS database [7, 8].

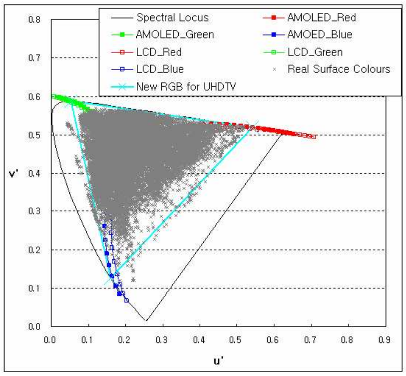


Figure 2. *The newly proposed RGB primaries for UHDTV that are indicated by cyan crosses.*

Table 1: The u′v′ chromaticity coordinates of the new RGB primaries derived for UHDTV.

Primary	u′	v′
Red	0.5399	0.5190
Green	0.0529	0.5867
Blue	0.1599	0.1256

The new RGB-primary set was evaluated in terms of gamut-coverage and -efficiency. In the computation of the gamut-coverage and -efficiency, reference gamut was firstly established from the real surface colors (Pointer and SOCS database) and the reproducible colors by the RGB primaries of the AMOLED [10], the LCD [10], a Digital-Cinema Reference Projector [11], and three standard color spaces (ITU-R BT.709 [3], Adobe RGB [12], and NTSC [13]). The gamut-coverage and -efficiency were computed using Eq. (1) and Eq. (2) respectively in three-dimensional CIELAB space. The segmentation maxima method was adopted to calculate the gamut boundary from which a gamut volume was obtained [14]. In the computation of the CIE $L^*a^*b^*$ values, D65 was used as a reference white. The gamut coverage indicates how much target gamut covers the reference gamut. The gamut efficiency shows how efficiently the target gamut encompasses the reference gamut and is related to the required bit-depth to encode RGB signals within the target gamut.

$$Gamut\ \ Coverage\ = \frac{target\ \ gamut \bigcap reference\ \ gamut}{reference\ \ gamut} \qquad (1)$$

where target gamut can be the gamut generated from the new RGB-primary set (or from the ITU-R BT.709’s RGB-primary set), reference gamut is the gamut created from the real surface colors, the flat panel displays and the standard color spaces, the numerator represents overlapped volume between the target gamut and the reference gamut, and the denominator indicates the reference gamut’s volume.

$$\text{Gamut Efficiency} = \frac{\text{referene gamut}}{\text{target gamut}} \tag{2}$$

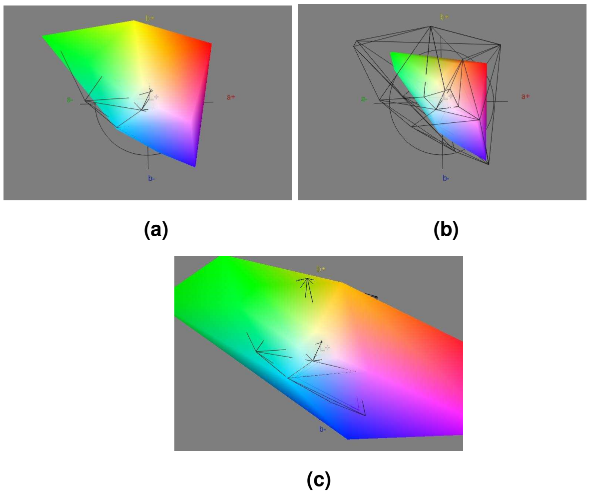
where the numerator and the denominator represent the reference gamut's volume and the target gamut's volume respectively. If the reference gamut's volume is larger than target gamut's volume, the inverse ratio of Eq. (2) is calculated for the gamut efficiency.

Table 2 shows the calculated gamut-coverage and -efficiency for the proposed RGB-primary set, the ITU-R BT.709's CRT-centric RGB-primary set, and a well-known xvYCC wide-gamut case in which non-specific RGB primaries were defined [15]. Figures 3(a) to 3(c) present three sets of gamut in the CIELAB space against the reference gamut representing real surface colors (symbolized by black wire) for these three examples. For the xvYCC case, only color-encoding methodology was addressed for enabling the colors located outside the gamut of ITU-R BT.709's to be encoded by extending RGB range of 0 – 1 to the infinite in its nonlinear function (RGB to R′G′B′). In Figure 3(b), most parts of the solid indicating ITU-R BT.709's gamut are completely encompassed by the black wire of the reference gamut, resulting in 51 % gamut coverage in Table 2. This suggests that the gamut of ITU-R BT.709 can contain about half of the real surface colors. In Figure 3(c), the solid indicating the gamut of xvYCC is much larger than the black wire of the reference gamut. Therefore, the gamut of xvYCC includes most of the real surface colors as is seen from the gamut coverage of 98 % in Table 2. However, since the gamut of xvYCC is unnecessarily large, it has the smallest gamut efficiency of 33 %. Comparing Figure 3(a) with Figure 3(c), the reference gamut is encompassed more efficiently by the proposed RGB-primary set in this study (i.e., 91 % vs 33 % in Table 2). In summary, the newly suggested RGB-primary set shows much larger coverage compared to the CRT-centric RGB-primary set and also higher efficiency against the wide-gamut xvYCC case.

Table 2: The computed results for the gamut-coverage and -efficiency.

	The new RGB-primary set suggested in this study	The CRT-centric RGB-primary set from ITU-R BT.709	xvYCC wide-gamut case
Gamut coverage	96 %	51 %	98 %
Gamut efficiency	91 %	51 %	33 %

On condition that as large as possible the gamut-coverage and -efficiency should be achieved by a newly derived RGB-primary set, the colors located in the border of cyan (green-blue) region in Figure 2 cannot be covered unless green primary is located outside the spectral locus, i.e., imaginary green color. Figures 1(b) and 1(c) show the gamut of the AMOLED and the LCD against the real-surface colors of Pointer and SOCS database. The highly saturated cyan colors that cannot be covered by the new RGB-primary set in Figure 2 appear also not to be included within the reproducible color ranges by the AMOLED and the LCD in figures 1(b) and 1(c). This indicates that the cyan region excluded from the gamut generated by the new RGB-primary set in Table 1 are hardly able to be reproduced by the AMOLED and the LCD. Thus, the gamut coverage of 96 % can be the maximum level achievable with the constraint that the new RGB primaries for UHDTV must be actual colors, not imaginary colors. Because only actual colors placed inside or on the spectral locus can be reproduced by physical displays.


(a) (b)

(c)

Figure 3. *Comparison of the reference gamut (black wire) in the CIELAB space with (a) the gamut formed by the RGB-primary set suggested in this study, (b) the gamut of ITU-R BT.709, and (c) the xvYCC wide-gamut case.*

A new color encoding scheme for UHDTV

Development of a new encoding method producing new luma (A) and color-difference ($C_{YB}C_{RG}$) signals

A new encoding scheme was developed using linear colorimetric signals, CIE *XYZ* tristimulus values [16]. The reason to choose *XYZ* signals instead of *RGB* signals is for constructing video signals based on a color space reflecting human visual characteristics. This may effectively lead to eliminate crosstalk problems that Recommendation ITU-R BT.709 holds.

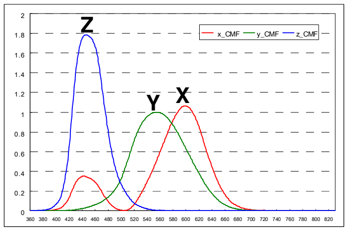


Figure 4. *The CIE 1931 Color Matching Functions.*

Figure 4 shows the CIE 1931 *xyz* color matching functions. The three curves corresponding to *XYZ* are seen to be overlapped one another. Against the real surface colors of Pointer and SOCS, correlation coefficients for each of *XY*, *XZ* and *YZ* pairs were 0.87, 0.56 and 0.5 [7, 8]. Two components (C_{RG} and C_{YB}) having red-green and yellow-blue color-difference information were therefore generated by separating X and Y, X and Z, and Y and Z signals. One component (A) having luminance information was formed from Y. The three signals $AC_{YB}C_{RG}$ derived in the present study correspond to $Y'C'_BC'_R$ defined in ITU-R BT.709 [3].

A simple block diagram is illustrated in Figure 5 showing the computation procedure from linear RGB signals to new luma (A) and color-difference ($C_{YB}C_{RG}$) signals for UHDTV systems. The conversion matrix transforming linear RGB to linear XYZ was calculated from the new RGB primaries in Table 1.

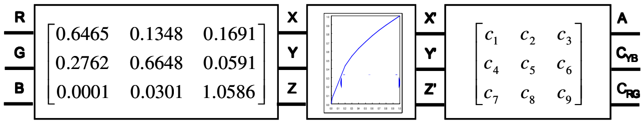


Figure 5. *A block diagram illustrating the new color encoding method for UHDTV systems.*

The linear XYZ encoding components were normalized using D65 reference white and then transformed onto nonlinear normalized $X'Y'Z'$ encoding components using a nonlinear power function introduced in Eq. (3). The straightforward type of power function as seen in Eq. (3) can also be used in addition to the power function with a linear portion at the toe that was defined in ITU-R BT.709.

$$E' = E^x \tag{3}$$

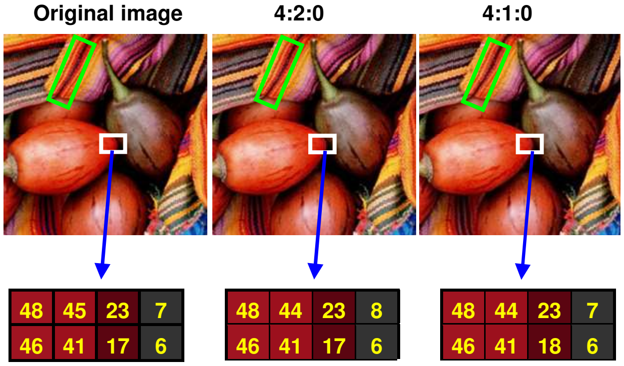
where E is each of normalized XYZ encoding components belonging to 0 – 1, and E' is each of nonlinear normalized $X'Y'Z'$ encoding components.

Luma and color-difference components ($AC_{YB}C_{RG}$) were finally generated from the nonlinear normalized $X'Y'Z'$ encoding components using the matrix composed of $c_1 - c_9$ coefficients. For example, if the same type of power function as ITU-R BT.709's is used, the $c_1 - c_9$ coefficients would be c_1=0, c_2=1, c_3=0, c_4=-0.325, c_5=-0.325, c_6=0.650, c_7=0.6476, c_8=-0.6472, and c_9=-0.0004. The matrix to produce $AC_{YB}C_{RG}$ signals was derived so as to satisfy the following three conditions: (1) minimization of correlation in each of AC_{YB}, AC_{RG}, and $C_{YB}C_{RG}$ signal pairs, (2) maintenance of A signal having luminance information regardless of subsampling $C_{YB}C_{RG}$ signals, and (3) for neutral colors, C_{YB} and C_{RG} = 0. The yellow-blue color-difference component C_{YB} was obtained by separating Z' from each of X' and Y'. The red-green color-difference component C_{RG} was derived by separating X' from each of Y' and Z'. When separating $X'Y'Z'$ encoding components one another, the $c_1 - c_9$ coefficients multiplied to individual $X'Y'Z'$ encoding components were optimized in order to fulfill the three constraints (1), (2), and (3).

In the derivation of the matrix having $c_1 - c_9$ coefficients, a huge data set was used to cover all the real surface colors and a wide range of color combinations occurring in natural scenes. A total number of 3,617,499 colors were collected from five categories. For the three categories – 'standard color space', 'flat panel display', and 'digital cinema', 4080 colors were sampled among the reproducible colors by the RGB primaries defined in each of ITU-R BT.709 [3], Adobe RGB [12], NTSC [13], the AMOLED [10], the LCD [10], and the digital cinema reference projector [11]. For the category of 'natural image', 36 images of diverse contents were selected from Corel image database. For the category of 'real surface color', Pointer and SOCS database was used [7, 8]. The correlation coefficients computed in each of three pairs of AC_{YB}, AC_{RG}, and $C_{YB}C_{RG}$ using this large data set of the five categories were all close to zero, i.e., 0.09, 0.15, and 0.07.

Measurement of crosstalk occurring between the new luma (A) and color-difference (CYBCRG) signals for UHDTV

An original image shown in Figure 6(a) was used to assess the level of crosstalk arising from the new derived luma and color-difference signal pairs (AC_{YB} and AC_{RG}). Only the two color-difference signals, $C_{YB}C_{RG}$, were subsampled in the format of 4:2:0 and 4:1:0 over an entire image. The subsampled $C_{YB}C_{RG}$ signals at 1/4 and 1/8 the original ratio and the A signals were then converted back to the RGB values with the original pixel sampling that construct the resultant images shown in figures 6(b) and 6(c). Bicubic interpolation method was applied to the conversion process back to the original pixel sampling for the subsampled $C_{YB}C_{RG}$ signals. The lightness values for the original image shown in Figure 6(a) and those for the $C_{YB}C_{RG}$-subsampled images shown in figures 6(b) and 6(c) were obtained using CIECAM02-UCS color appearance model [9]. The area represented by a white box in each of the original and the $C_{YB}C_{RG}$-subsampled images is shown in its magnified form (at the bottom of each image) with the calculated lightness values.



(a) (b) (c)

Figure 6. *The lightness values for the magnified area (indicated by a white box)* ***(a)*** *in the original image and in the output images that were constructed after subsampling C_{YB} and C_{RG} signals in the format of* ***(b)*** *4:2:0 and* ***(c)*** *4:1:0.*

The same original test image and the identical procedure for subsampling chrominance components were also used to estimate the amount of crosstalk occurring from $Y'C'_B$ and $Y'C'_R$ pairs in ITU-R BT.709. The reconstructed images after subsampling $C'_BC'_R$ signals in the format of 4:2:0 and 4:1:0 are viewed in figures 7(b) and 7(c) respectively.

The lightness values of the $C_{YB}C_{RG}$-subsampled images shown in figures 6(b) and 6(c) are almost equal to those of the original image seen in Figure 6(a) regardless of the subsampling format. As a result, the clear boundary of the red fruit against its dark background (indicated by the white box) and the apparent dark stripe line against its neighboring orange-yellow background (indicated by a green box) is remained in the $C_{YB}C_{RG}$-subsampled images compared to the original image. On the contrary, significant lightness discrepancies in the right-side four darker pixels and varied dark stripe line were found in Figure 7(c) compared to Figure 7(a). For the original image seen in Figure 7(a), a clear boundary of the red fruit can be viewed due to the large lightness-difference between the red fruit and its adjacent dark background. This tendency is not remained for the $C'_BC'_R$-subsampled image seen in Figure 7(c), leading to a blurred boundary. The lightness comparison results given in figures 6(a) to 6(c) indicate that the new encoding scheme can offer the luma and color-difference signals having inappreciable crosstalk. In other words, it is believed that A signal contains tiny chrominance information, and C_{YB} and C_{RG} signals have inconsiderable luminance information.

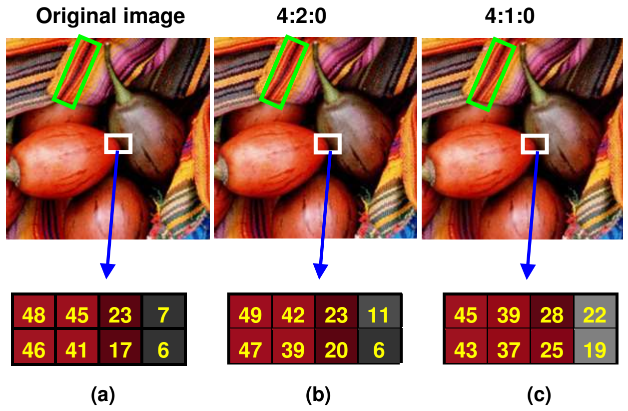


Figure 7. *The lightness values for the magnified area (indicated by a white box) (a) in the original image and in the output images that were constructed after subsampling* C'_B *and* C'_R *signals in the format of (b) 4:2:0 and (c) 4:1:0.*

The influence of different video signals on image compression

As proved in the previous section, the newly proposed encoding method for UHDTV systems produced much less crosstalk than the conventional encoding scheme of ITU-R BT.709 which is currently used for HDTV systems. The effect of this difference on the quality of compressed image was thus evaluated using two test images that are viewed in Figure 8(a). After subsampling two sets of color-difference components ($Y'C'_BC'_R$ and $AC_{YB}C_{RG}$) using 4:2:0 format, H.264 was applied to these subsampled images with five different compression rates which were controlled by the QPI (Quantization Parameter for Intra Picture) values of 22, 25, 27, 32 and 37 [17]. A use of larger QPI values results in more compressed images.

Assuming that color difference signals do not include luminance information, the lightness difference between the original image and its chroma subsampled image should occur only due to rounding errors. The lightness (CIELAB L^*) difference in terms of PSNR (Peak Signal to Noise Ratio) was therefore chosen to assess the amount of crosstalk in the examination of the impact of different signal format on the quality of compressed image. Observers were asked to select the QPI level for the compressed image in the $AC_{YB}C_{RG}$ domain that was perceived to have similar or slightly better image quality compared with the compressed image in the $Y'C'_BC'_R$ domain at the QPI level of 22. The PSNR-lightness values were calculated between the original and its compressed image for each of two test images at five QPI values of 22, 25, 27, 32 and 37. Figure 8(b) plots the PSNR-lightness values against the bit-rates obtained after compressing 4:2:0 subsampled images. The blue data points represent the results in the $AC_{YB}C_{RG}$ domain whereas the black data points in $Y'C'_BC'_R$ domain.

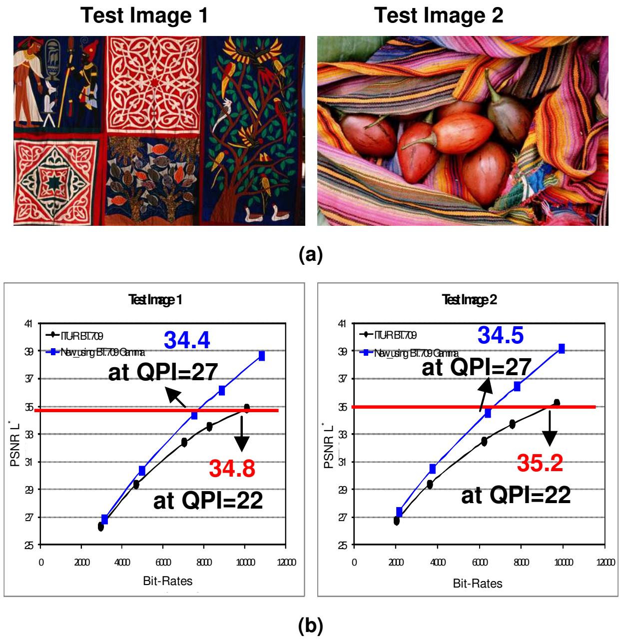


Figure 8. (a)*Two test images used and* ***(b)*** *the PSNR-lightness values against the bit-rates calculated after compressing 4:2:0 subsampled images.*

The compressed images using $AC_{YB}C_{RG}$ signals at the QPI value of 27 appeared to have almost identical image quality to those using $Y'C'_BC'_R$ signals at the QPI value of 22 for the two test images. A red line was drawn in Figure 8(b) over the two corresponding images that were observed to have almost identical subjective quality for each of two test images. This line represents that the two corresponding images have quite similar PSNR-lightness values. These results mean that when subsampling and compression processes are conducted in the $AC_{YB}C_{RG}$ domain, more compressed images at larger QPI value can offer resemblance in perceived image quality compared to the case where those processes are performed in the $Y'C'_BC'_R$ domain. Finally, improved compression efficiency is expected by reducing bit-rates when the new video signals of $AC_{YB}C_{RG}$ having less crosstalk than $Y'C'_BC'_R$ signals are used on condition that almost identical perceived quality is obtained. This point will further be examined using moving test images.

Conclusion

The current work introduced a new RGB-primary set and a new color encoding-scheme that are believed to be suitable for UHDTV program production. The new RGB-primary set was derived in favor of inclusion of real-world surface colors and in consideration of the characteristics of AMOLED and LCD using which UHDTV programs would be presented. The new encoding scheme was developed from XYZ tristimulus values reflecting human visual properties and aimed at producing luma and color-difference signals that were as much as possibly orthogonal.

The evaluation results showed that much less crosstalk occurred between the luma and color-difference signals of $AC_{YB}C_{RG}$ created by the new encoding method compared to those signals of $Y'C'_BC'_R$ produced by ITU-R BT.709. Additionally, the new encoding method was also evaluated in connection with a compression tool of H.264. The use of $AC_{YB}C_{RG}$ signals having insignificant crosstalk was shown to be able to decrease bit-rate compared to $Y'C'_BC'_R$ signals of ITU-R BT.709 assuming that similar image quality was perceived. This observation means that when 4:2:0 chroma subsampling format is applied to UHDTV program transmission after finishing program production, the new encoding method can provide enhanced image quality to end-users than ITU-R BT.709. The influence of the newly developed luma and color-difference signals on image data redundancy will be further investigated using moving images.

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