On the Relationship of Color Image Compression and Gamut: JPEG and JPEG2000

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Abstract

Image compression schemes, such as JPEG and JPEG2000, degrade the quality of a reconstructed image due to their lossy characteristics. Among such degradation factors, color bleeding is particularly visible around colors between highly contrasting chrominance areas. This phenomenon is a result of the abrupt truncation of high-frequency components due to coarse quantization and subsampling of the chrominance channel, which appears as color smearing owing to spurious colored oscillations in the reconstructed image. Consequently, a change of color information, such as loss of the chrominance component and corresponding color smearing phenomenon, affects the gamut characteristic of the reconstructed image. Accordingly, this paper investigates the relationship between the compression ratio and the gamut area for a reconstructed image when using JPEG and JPEG2000. Eighteen color samples from the Macbeth ColorChecker are initially used to analyze the relationship between the compression ratio and the color bleeding phenomenon, i.e. the hue and chroma shifts in the a^*b^* color plane. When increasing the compression, color bleeding becomes apparent between adjacent colors samples, resulting in a loss of chroma in relation to the original color. However, some original colors exhibit a chroma increase due to spurious colored oscillations along the color sample boundaries. In addition, a hue shift appears along the direction connecting adjacent colors samples. Twelve natural color images, divided into two groups depending on four color attributes, are also used to investigate the relationship between the compression ratio and the variation in the gamut area. For each image group, the gamut area for the reconstructed image shows an overall tendency to increase when increasing the compression ratio, similar to the experimental results with the Macbeth ColorChecker samples. However, with a high compression ratio, the gamut area decreases due to the mixture of adjacent colors, resulting in more grey.

Introduction

In the case of limited transmission bandwidth or storage space at the receiver end, image compression schemes, such as JPEG[1] and JPEG2000,[2] facilitate the transmission and storage of data in an efficient form by reducing the redundancy of image data. However, due to the irreversible nature of lossy compression, these schemes also introduce various types of distortion, such as blockiness, blurriness, and noise, in the reconstructed image at high compression rates.[3-5] Since a natural trade-off exists between the level of compression and the quality of the reconstructed image, effective compression techniques attempt to maximize either the compression with no discernible degradation in quality or the quality with a specified compression ratio.

Many studies have already examined the image distortions related to JPEG and JPEG2000,[3-5] and presented both quality metrics for measuring such artifacts and practical approaches for improving the perceptual quality of a decompressed image.[3,6,7] Nonethelss, in case of sacrificing large amounts of color information for effective data reduction, using the premise that the human visual system is less sensitive to the chrominance component, research on color artifacts has only recently been receiving attention.[8-11] At high compression ratios, a decompressed image suffers from color artifacts, which are caused by the subsampling of the chrominance channels in JPEG and multi-resolution nature of the wavelet transform in JPEG2000, along with the coarse quantization of the chrominance component in both algorithms. Color bleeding is particularly visible around colors between highly contrasting chrominance areas, and appears as color smearing due to spurious colored oscillations in the reconstructed image.[8-11] Thus, a change in the color information, such as a loss of the chrominance component in the compression process and corresponding color smearing, affects the image gamut characteristic. Hence, since the image gamut is related to the overall color richness of a given image, investigating the image gamut may be an effective metric for evaluating the perceptual quality fidelity of a decompressed image compared to the original image.

Accordingly, this paper investigates the relationship between the compression ratio and the gamut area for a decompressed image using JPEG and JPEG2000. To analyze the relationship the between compression ratio and the color bleeding phenomenon, i.e. the hue and chroma shift in the a^*b^* color plane, eighteen color samples from the Macbeth ColorChecker are initially used as representative colors for all colors due to their uniform distribution in CIELAB color space. Based on the color information shift for the representative color samples, twelve natural color images, classified into two groups depending on four color attributes, are also used to investigate the relationship between the level of compression and the variation in the gamut area for the reconstructed images. After determining the gamut areas for the decompressed images in relation to the compression ratio, the optimal least square method is applied to approximate the relationship for each image group. Finally, fitting curves are presented for an equation minimizing the error between the real data, the gamut area for the decompressed images, and its corresponding approximated values.

Color Shift Phenomenon for Representative Color Samples

Color smearing caused by color leakage from lossy compression is visible at strongly contrasting color boundaries, resulting in a loss of saturation generally at higher compression

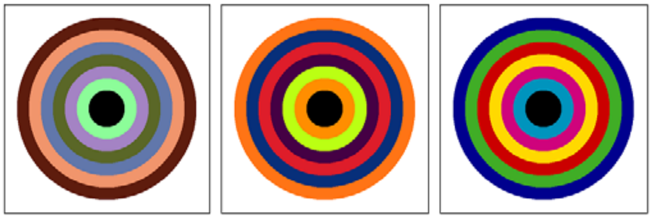
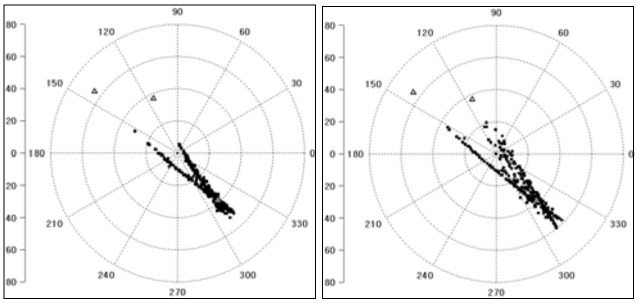
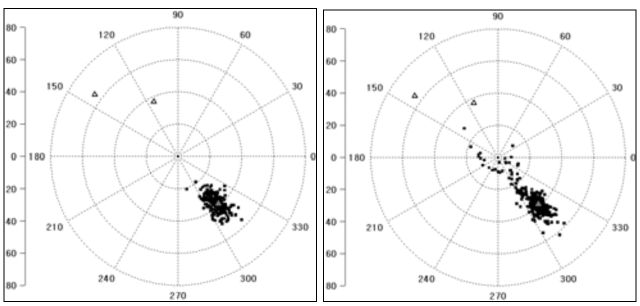


***Figure 1**. Three synthetic circle bar images.*



(a) A compression ratio of 28:1 (b) A compression ratio of 71:1



(c) A compression ratio of 28:1 (d) A compression ratio of 71:1

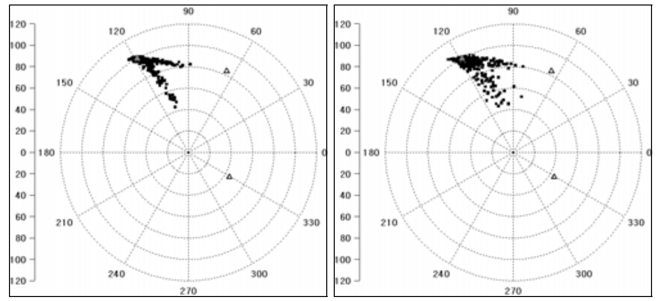
***Figure 2**. Color shift in 5th outer circle region for left image in Fig. 1: (a) and (b) with JPEG, and (c) and (d) with JPEG2000.*

ratios.[11] While spurious colored oscillations as a result of the ringing phenomenon in the chrominance channel cause a slightly overshoot of color information, the saturation of the reconstructed image is not necessarily decreased as the compression ratio increases. Therefore, to examine the hue and chroma shift phenomenon of colors in relation to the compression ratio in the a^*b^* color plane, three synthetic test images using color samples from each row of the Macbeth ColorChecker were initially designed, as shown in Fig. 1. The test images were composed of a circular color bar so as to emphasize the color shift after compression when using JPEG, which is based on a discrete cosine transform (DCT) of 8x8 pixel blocks, and JPEG2000, which is based on a discrete wavelet transform (DWT) of rectangular non-overlapping blocks (tiles).[11]

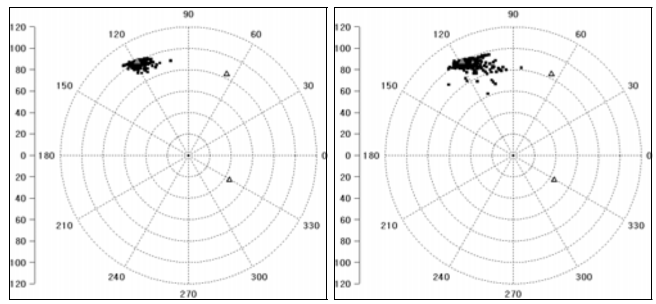
In this experiment, the compression ratios were set at 28 and 71 as the lower and higher compression ratio, respectively, corresponding to 0.86 bits per pixel (bpp) and 0.34 bpp, respectively, as summarized in Table1. To provide visual evidence of the color shift phenomenon, the hue angle and chroma position

Table 1: Compressed bit rates used in experiment.

Lossy quality	
Higher	Lower
0.86 bpp	0.34 bpp



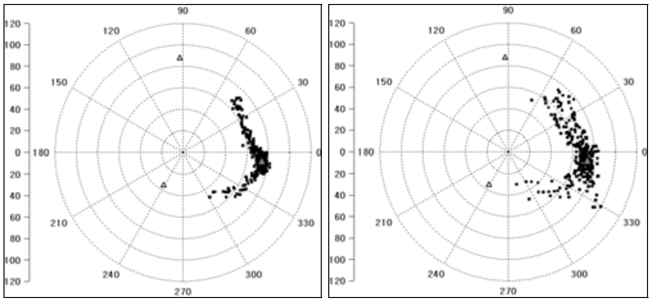
(a) A compression ratio of 28:1 (b) A compression ratio of 71:1



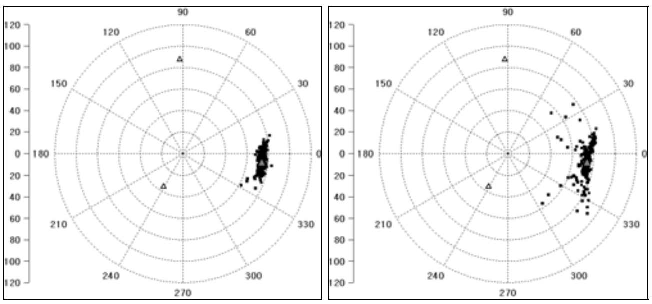
(c) A compression ratio of 28:1 (d) A compression ratio of 71:1

***Figure 3**. Color shift in 5th outer circle region for middle image in Fig. 1: (a) and (b) with JPEG, and (c) and (d) with JPEG2000.*

for all the colors in the 5th outer circle region in each reconstructed test image are displayed in Figs. 2 to 4. The numerical values in the graphs are the hue angle for a degree unit, while the scales on the left represent the chroma in the a^*b^* color plane. Meanwhile, to investigate the magnitude and direction of the color shift, the hue and chroma of an original (gray triangle) and two neighbor (empty triangle) colors in the uncompressed test image are also marked in the figures. The color shift phenomenon in the reconstructed images is then apparent as color smearing between the original color and the two neighbor colors, as shown in Figs. 2 to 4. Figs. 2 to 4 also show that as the compression ratio increases, most of the colors produced by color smearing from adjacent regions exhibited a loss of chroma, whereas some of the colors produced by spurious colored oscillations along a strong contrast colored edge exhibited an increased chroma. In addition, the hue of these colors was distributed along the direction connecting the adjacent two colors. The magnitude of the color shift increased as the compression ratio increased, and when comparing JPEG and JPEG2000, the color bleeding caused by JPEG was more obvious than that caused by JPEG2000. It was also found that the chroma increase in Fig. 3 was much small compared to that in Figs. 2 and 4, as the chroma for the original color (gray triangle) in Fig. 3 was relatively high. Although the color shifts are only described for

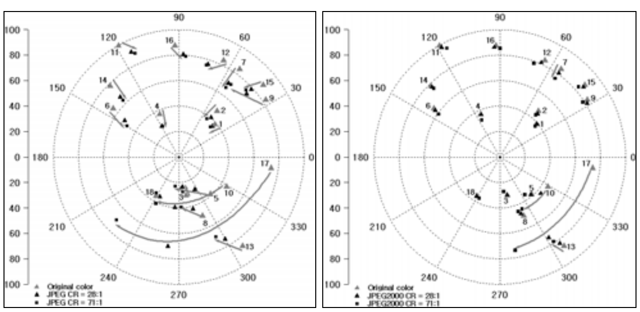


(a) A compression ratio of 28:1 (b) A compression ratio of 71:1



(c) A compression ratio of 28:1 (d) A compression ratio of 71:1

***Figure 4**. Color shift in 5th outer circle region for right image in Fig. 1: (a) and (b) with JPEG, and (c) and (d) with JPEG2000.*



(a) (b)

***Figure 5**. Average shift of hue angle and chroma for eighteen colors from Macbeth ColorChecker: (a) with JPEG and (b) with JPEG2000.*

three color samples, the other colors also exhibited a similar appearance.

Fig. 5 shows the average shift of the hue angle and chroma due to color bleeding in the eighteen color regions, where the numerals next to the original color (gray triangle) represent the order of the colors in the Macbeth ColorChecker from left to right and from top to bottom. The dark triangles and dark squares indicate the results corresponding to a compression ratio of 28 and 71, respectively, while the gray arrows indicate the locus of the color shift according to the increase in the compression ratio. Except for purple (number 10) and magenta (number 17), which were placed around the purple boundary in the xy chromaticity diagram, the rest of the colors exhibited a similar aspect in each graph.

Classification of Natural Color Images

The experiments using the synthetic test images revealed that the color smearing in the reconstructed images caused a shift in the hue and chroma, although there was a difference in the magnitude and direction according to the color. In particular, the chroma increase in the decompressed images was affected by the chroma characteristic of the color in the original image. Thus, to investigate the gamut variation of reconstructed natural color images according to the level of compression, twelve natural color images were also tested. These images were divided into two groups depending on four color attributes, such as the image gamut size, colorfulness,[12,13] spatial frequency of the chrominance channel *Cb* and *Cr*,[14] and number of unique colors in RGB color space.

First, the gamut size of the original image was calculated as the area of the gamut boundary described by GBD in the a^*b^* color plane. Since GBD is obtained using the Segment Maxima Method that does not have a convexity limitation, it represents the image gamut almost accurately.[15] Here, the size of image gamut was defined as the area of a polygon consisting of a^* and b^* coordinates on the gamut boundary.

Second, it is generally well-known that the colorfulness of an image containing a lot of chromatic details is reduced at a higher compression ratio. Since this loss of colorfulness may be related to the variation of the image gamut, colorfulness was also used as one of the measures for classifying the natural images. Hence, the colorfulness M_c was calculated using a computationally more efficient approach in a simple opponent color system, defined as follows:[12-13]

$$\begin{aligned} rg &= R - G \\ by &= \frac{1}{2}(R+G) - B \\ M_c &= \sqrt{\sigma_{rg}^2 + \sigma_{by}^2} + 0.3 \times \sqrt{\mu_{rg}^2 + \mu_{by}^2} \end{aligned} \tag{1}$$

where, σ and μ are the standard deviation and mean of the pixel cloud along directions rg and by, respectively.

Third, the color artifacts in a reconstructed image depend on the image characteristics and scene content at the same compression ratio. Namely, natural images containing large spatial frequency areas in the chrominance channel experience large errors due to coarse quantization of the frequency coefficients, as well as the subsampling process, resulting in more color artifacts in the decompressed image. Therefore, the spatial frequency M_{sf} was also adopted as one of the metrics for classifying the natural test images, which was calculated as follows in the chrominance channel *Cb* and *Cr*:[14]

$$\begin{aligned} M_{sf} &= \sqrt{R^2 + C^2} \\ R^2 &= \frac{1}{MN} \sum_{i=0}^{M-1} \sum_{j=0}^{N-2} \left(x_{i,j} - x_{i,j+1}\right)^2 \\ C^2 &= \frac{1}{MN} \sum_{i=0}^{M-2} \sum_{j=0}^{N-1} \left(x_{i,j} - x_{i+1,j}\right)^2 \end{aligned} \tag{2}$$

where R and C are the spatial frequency along the row and column direction, respectively. $x_{i,j}$ denotes the spatial coordinates

(a)

(b)

Figure 6. *Classification of twelve test images: (a) group 1 and (b) group 2.*

Table 2: Classification of natural test images according to four attributes.

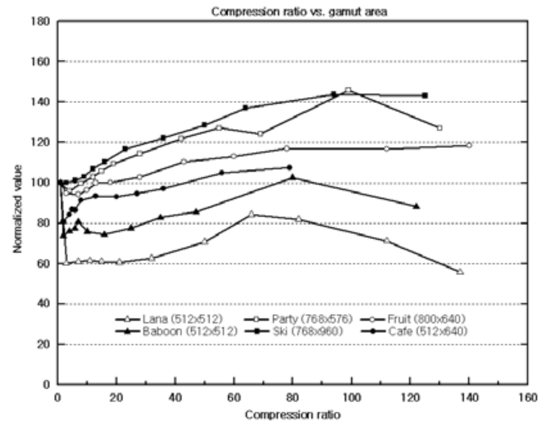
Group	attribute / Image	Gamut area (a*b* plane)	Colorful-ness	Spatial frequency		Number of unique color
				Cb	Cr	
Group 1	Lena	9658.7	64.8	5.6	5.4	56.6%
	Baboon	20846.4	85.8	14.2	13.3	87.9%
	Party	19532.6	46.7	5.1	4.8	33.7%
	Ski	27398.7	92.5	8.0	9.1	40.4%
	Fruit	28664.8	104.4	6.5	7.5	47.4%
	Café	32606.8	95.8	17.7	15.3	61.6%
Group 2	Cap	9292.0	46.8	2.1	1.8	9.2%
	Girl	2955.8	50.1	1.3	2.9	8.1%
	House1	4434.8	37.0	2.2	2.5	13.9%
	House2	2468.9	25.0	2.2	2.3	12.3%
	Light house	5035.3	29.6	1.7	1.5	6.4%
	Motor cycle	11839.0	34.4	2.9	2.7	16.6%

for the *Cb* and *Cr* image, and M and N are the numbers of pixels in the horizontal and vertical direction, respectively.

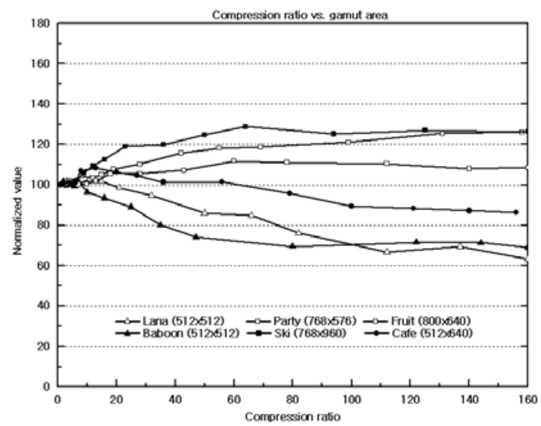
Finally, in this paper, a unique color was defined as a pixel with a mutually different R, G, and B value. Plus, the number of unique colors is related to the overall color richness of an image, which in this case was calculated as a percentage of the total number of pixels to remove the influence of the image size. The results after classifying the twelve natural color images according to the above-mentioned four attributes are shown in Fig. 6 and Table. 2. The test images belonging to group 1 had larger values those in group 2 with regard to all four attributes. Even though the *Lena* image had a slightly smaller gamut area than the *Motorcycle* image, it was still included in group 1 due to significant difference in the other three attributes.

Relationship between Image Gamut and Compression Ratio

In the case of JPEG, the quantization is defined as the division of each DCT coefficient by its corresponding quantization step size, followed by rounding to the nearest integer, where the quantization step size is controlled by weighting the default quantization matrix for the luminance and chrominance component and the weighting depends on the quality factor.[16] Thus, since a variable compression rate can be achieved by simply scaling the quality factor, in this paper, the quality factor was specified on a scale between 1 and 100, where a factor of 100 represented the lowest compression rate and a factor of 1 was the highest. Meanwhile for JPEG2000, the compression level of an image can be controlled by the quantization step size. For each subband after DWT, the quantization step size is used to quantize all the coefficients in that subband, where the quantization step size is controlled by combining the dynamic range of that subband and two unsigned integers.[16] Therefore, in this paper, the compression ratio for JPEG2000 was specified on a scale between 1 and 160.



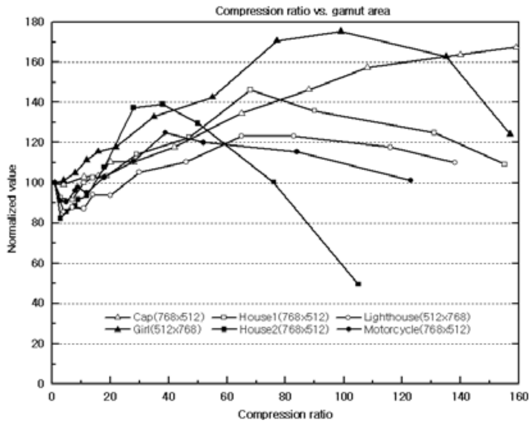
(a)



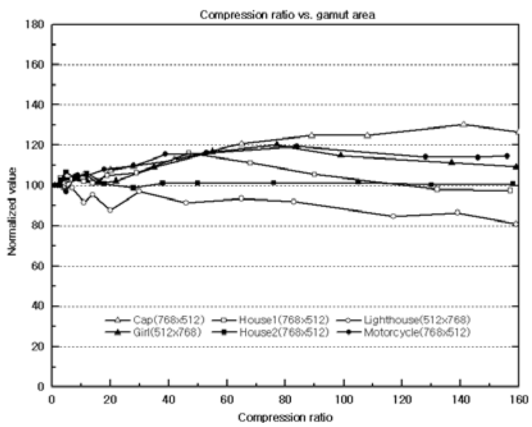
(b)

Figure 7. *Change in gamut size according to compression ratio for group 1 images: (a) with JPEG and (b) with JPEG2000.*

For the natural color images categorized into group 1 and group 2, graphs showing the gamut areas for the decompressed images according to the compression ratio are displayed in Figs. 7 and 8, respectively. The vertical axes in all the graphs represent the normalized gamut area, which was calculated as a percentage of the gamut area for the original image for easy comparison. When compressed using JPEG, the gamut area for the reconstructed images more fluctuated, as shown in Figs. 7(a) and 8(a). In the case of the images with a large original gamut area, such as *Café* and *Fruit* in group 1, the change in the gamut area for the

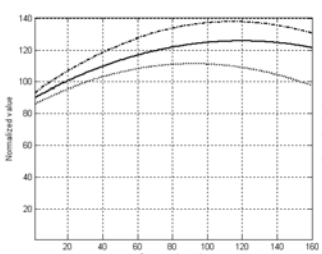


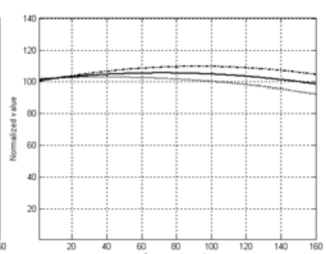
(a)



(b)

Figure 8. *Change in gamut size according to compression ratio for group 2 images: (a) with JPEG and (b) with JPEG2000.*

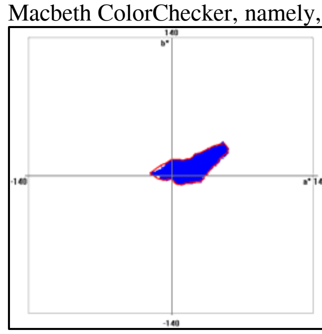


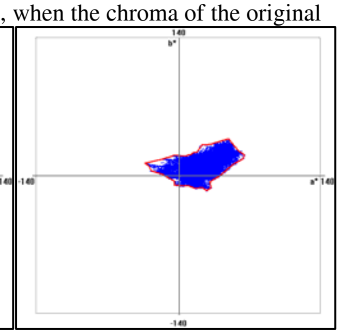


(a) (b)

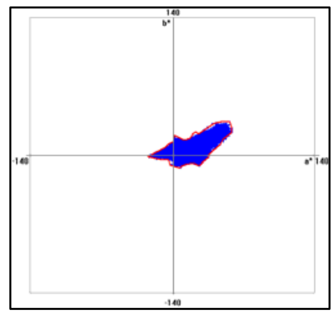
Figure 9. *Fitting curves: (a) with JPEG and (b) with JPEG2000.*

reconstructed image compared to that for the original image was relatively smaller than the change exhibited by the other images, even with an increase in the compression ratio, as shown in Fig. 7. Conversely, the images with a small original gamut area, such as *House2* and *Girl* in group 2, exhibited a significant fluctuation in the gamut size of the reconstructed image when increasing the compression ratio, as shown in Fig. 8. These results also reflected the experimental results when using the color samples from the Macbeth ColorChecker, namely, when the chroma of the original





(a) (b)



(c)

Figure 10. *Gamut for Girl image: (a) original image, (b) decompressed image using JPEG, and (c) decompressed image using JPEG2000.*

color was high, the chroma increase caused by spurious colored oscillation was small.

The optimal least square method was also applied to approximate the relationship between the compression ratio and the change in the image gamut size. For each group of images, fitting curves for a second-order equation minimizing the error between the real data, the gamut area for the decompressed images, and its corresponding approximated value were deduced as follows:

$$\begin{aligned} y &= -0.0026x^2 + 0.61x + 89.5 \quad &\text{for all images in JPEG} \\ y &= -0.0030x^2 + 0.56x + 85.64 \quad &\text{for group1 images in JPEG} \\ y &= -0.0035x^2 + 0.79x + 92.4 \quad &\text{for group2 images in JPEG} \end{aligned} \tag{3}$$

$$\begin{aligned} y &= -0.0009x^2 + 0.13x + 100.88 \quad &\text{for all images in JPEG2000} \\ y &= -0.0007x^2 + 0.055x + 101.7 \quad &\text{for group1 images in JPEG2000} \\ y &= -0.0011x^2 + 0.21x + 99.99 \quad &\text{for group2 images in JPEG2000} \end{aligned} \tag{4}$$

In Eqs. (3) and (4), x was the compression ratio specified on a scale between 1 and 160, while y was the normalized gamut area for the reconstructed image, which was calculated as a percentage of the gamut area for the original image. Fig. 9 shows the fitting curves corresponding to Eqs. (3) and (4). Here, the solid line indicates the modeling graph for all twelve natural color images, the dotted line the six images contained in group 1, and the dash-dot line the six images belonging to group 2. The modeling graphs show that the image gamut size decreased after a gradual increase when increasing the compression ratio, and finally became smaller than the gamut size of the original image at a higher compression ratio. Thus, it would seem that the initial increase in the gamut size when changing from a lower to a medium compression ratio resulted from a chroma increase due to spurious colored oscillations in the reconstructed image, whereas the decrease in the gamut size with a higher compression ratio was caused by the mixture of colors from adjacent regions, resulting in more grey. When comparing JPEG and JPEG2000, the graphs had a similar appearance overall, although there was a difference in the slopes of the graphs. Namely, the variation of the gamut size with JPEG was more noticeable than that with JPEG2000 at a same compression ratio.

To provide a visual comparison of the change of gamut size, Fig. 10 shows the gamuts for the original *Girl* image and reconstructed images after compression using JPEG and JPEG2000 with a compression ratio of 77. After JPEG, the gamut size for the decompressed image increased approximately 70% compared to that for the original image, whereas after JPEG2000, the gamut size for the decompressed image only increased 20%. These results were also confirmed in Fig. 8.

Conclusion

Color bleeding caused by a change of color information, such as subsampling and coarse quantization in the chrominance channel, affects the gamut characteristic of a decompressed image. Therefore, this paper investigated the relationship between the compression ratio and the gamut area for an image compressed using JPEG and JPEG2000. To examine the shift phenomenon of hue and chroma in relation to the compression ratio, three synthetic images based on eighteen color samples from the Macbeth ColorChecker were used in the experiments. Using the experimental results, twelve natural color images, classified into two groups depending on four color attributes, were then used to investigate the relationship between the level of compression and the variation in the gamut area for the reconstructed images. Finally, fitting curves were presented for an equation approximating the relationship between the compression ratio and the image gamut area. For each image group, the gamut area for the reconstructed image showed an overall tendency to increase when increasing the compression ratio, due to a chroma increase resulting from spurious colored oscillations. However, with a high compression ratio, the gamut area tended to decrease due to the mixture of adjacent colors, resulting in more grey.

In our future work, it is necessary to consider the technique for removing the color bleeding phenomenon presented in compressed color images. Also, establishing the effects of the gamut for a decompressed image on perceptual image quality will be another important target of future investigation.

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