COLOR IMAGE COMPRESSION USING ADAPTIVE COLOR QUANTIZATION

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ABSTRACT

The objective of perceptual compression scheme is to remove the visual redundancy of images and maintain the perceptual quality of decoding result. In this paper, a perceptually adaptive color quantizer is designed for color image compression in wavelet domain. The quantization step sizes of three color components for each coefficient are adaptively adjusted by the estimated error visibility thresholds for achieving transparent coding at low bit rate. Based on the proposed color visual model, the error visibility thresholds are estimated by quantifying the perceptual redundancy in color spaces. The visual model is built on defining a perceptually indistinguishable region for each color in a color space by mapping colors, which are barely distinguishable from the target color in a perceptually uniform color space (PUCS), to the target color space. The simulation results show that the proposed scheme is able to achieve the perceptually lossless color image compression at low entropies.

1. INTRODUCTION

By a growing demand for representing high-quality color images as the resource of storage or transmission bandwidth is limited, color image compression algorithm that is transparent to human visual perception is highly expected. However, most of the existing methods for image coding are concentrated on grayscale visual information [1-3]. Encoding the color components of color images separately by these schemes does not guarantee optimization of performance and efficiency.

In [4], the interdependence between different color components in luminance and chrominance (LC) space is successfully applied to the design of embedded data rate scalable coding algorithm, in which a spatial orientation tree links not only the frequency bands but also the color channels for scanning the wavelet coefficients. Nadenau *et al.* present the wavelet-based color image compression by exploiting the contrast sensitivity function (CSF) [5]. The method implements the CSF measure over spatial frequency for luminance and chrominance components into the task of noise spectrum shaping and achieves a visually optimal compression quality. Nevertheless, these coding schemes fail to offer color quantizers for both luminance and chrominance components.

One promising approach is to quantify the perceptual redundancy in the form of error visibility thresholds and use the derived threshold to control the quantization strategy. In the existing research, Watson *et al*. [6] construct a mathematical model for evaluating DWT noise detection thresholds based on the visual model that incorporates frequency and orientation sensitivity and contrast masking of human visual system (HVS). By exploiting one fixed step size for a whole subband in terms of the corresponding noise detection thresholds, author designs a fixed quantization matrix for all color images in the *YCbCr* color space. The problem that arises when applying the matrix to wide range of complexities of color images is that the image dependent estimation of perceptual redundancies is required for adaptively controlling the quantization and dequantization strategy in order to minimize the perceptual distortion.

This paper presents an image dependent color quantizer for DPCM coder to increase the performance of quality and bit rate. The quantization strategy is tuned in a way that the quantization step size is adjusted to the *just noticeable difference* (JND), which is estimated by the proposed visual model accomplishing with wavelet decomposition. In LL band, the visual model is built on defining a perceptually indistinguishable region for each color in *YCbCr* color space by mapping colors, which are barely distinguishable from the target color in a perceptually uniform color space. As the region is determined, the perceptual redundancy in terms of error visibility thresholds for three color components of each coefficient can be defined. The perceptual redundancies of other subbands are then adaptively evaluated by the amount of contrast masking which is varied with the local frequency and orientation of the considered image.

2. COLOR PERCEPTUAL REDUNDANCY

Color is a visual perception of the light in the visible region of the electromagnetic wave spectrum incident on the retina. Since the retina has three types of photoreceptors that respond to different parts of the visible spectrum, three components are necessary and sufficient to specify a color. With colorimetric coordinates for specifying each color in a color space, the perceptual redundancy of a color pixel can be quantitatively measured by calculating the distance between the target color and each of the colors that are barely different from the target color. However, colors in many color spaces, such as *RGB*, *XYZ*, *YUV*, and *YCbCr* are not uniformly distributed in the sense that Euclidean distances between colors are not closely correlated with color differences perceived by humans. That is, the colors that are indiscernible from the target color form a perceptually indistinguishable region with irregular shape

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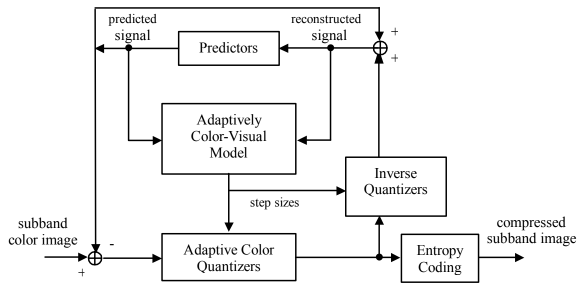


Fig. 1 Block diagram of the perceptual tuned coder.

in these color spaces. The perceptually indistinguishable region always provides large amount of perceptual redundancy which can be used to improve the performance of image processing applications. It also explains why a color visual model should be investigated to conveniently define the perceptually indistinguishable region for quantifying the perceptual redundancy of colors.

The spaces *CIELAB* and *CIELUV* recommended by International Commission on Illumination (*CIE*) in 1976 were such perceptually uniform color spaces through nonlinear transformations of tristimulus *XYZ* as to overcome the non-uniformity of color spaces that had been discussed by MacAdam and others from the early 1940s [7]. Even though *CIELAB* is not a perfect uniform color space, the color distance between two colors is considerably correlated with the perceptual difference. If a color space is perfectly uniform in color metric, the locus of colors which are not perceptually different from a given color forms a sphere with a radius equal to the so-called *just noticeable color difference* (JNCD) [8-9]. By exploiting the sphere of JNCD in the uniform color space and the transformation of color spaces, the perceptually indistinguishable region of the color in target color spaces can be conveniently defined.

3. IMAGE COMPRESSION USING COLOR QUANTIZATION

The coding block diagram is extended from [3] for color images and shown in Fig. 1. The adaptively color-visual model used to tune quantization step sizes is depicted in Fig.2. In the coding scheme, the input color image is first transformed to YCbCr color space and decomposed into 10 subbands by linear-phase 9/7 filters. The transformed coefficients in each subband b of the three color channels can be represented by $r_{\mathrm{Y}}(b,x,y)$, $r_{\mathrm{Cb}}(b,x,y)$ and $r_{\mathrm{Cr}}(b,x,y)$, respectively, where x, y are the horizontal and vertical index, respectively. The subband number is shown in Fig. 3. Each component is coded by DPCM separately and scanned row-by-row in the order of increasing subband number b at (x,y).

The issue in quantifying the perceptual redundancy is that the perceptually indistinguishable region for each color in the target color space needs to be defined to ensure the visibility threshold of each channel. In our model, we develop an algorithm for finding color samples that are located close to the surface of the JNCD sphere

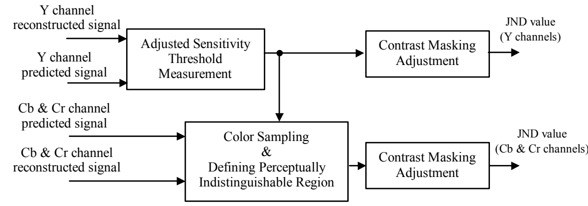


Fig. 2 Block diagram of the proposed adaptively color-visual model.

around the target color in the *CIELAB* and establish a criterion for defining a perceptually indistinguishable region around the target color in the working color space from those sampled JNCD colors transformed from the *CIELAB*. Since the luminance CSF is significantly higher than the chromatic CSFs, the sampling algorithm is constrained in the sense that the luminance differences between sample colors and the target color should be smaller than the perceptibility threshold of luminance component. It is believed that the color samples with corresponding color differences set to be luminant JND of target color can be used to closely map to the perceptually indistinguishable region.

3.1 Luminance detection threshold measure

The estimated JND value of luminance component at location (b,x,y) is conducted as

$$\hat{t}_{\mathrm{Y},JND}(b,x,y) = t_{\mathrm{Y},D}(b,x,y)\cdot m_{\mathrm{Y},C}(b,x,y) \qquad (1)$$

where $t_{\mathrm{Y},D}(b,x,y)$ is the adjusted sensitivity threshold and $m_{\mathrm{Y},C}(b,x,y)$ is the contrast masking adjustment.

The adjusted sensitivity threshold refers to the just visible level of stimuli over a background with uniform intensity. It is given by

$$t_{\mathrm{Y},D}(b,x,y) = t_{base}(b)\cdot a_{\mathrm{Y},D}(\hat{r}_{\mathrm{Y}}(0,i,j))$$
$$\text{for } i=\left\lfloor \frac{x}{p}\right\rfloor, j=\left\lfloor \frac{y}{p}\right\rfloor, p=2^{(\lceil b/3\rceil-1)} \qquad (2)$$

where $t_{base}(b)$ is the based sensitivity threshold and $a_{\mathrm{Y},D}(\hat{r}(0,i,j))$ is the luminance masking adjustment by considering the corresponding reconstructed coefficient $\hat{r}_{\mathrm{Y}}(0,i,j)$ (predicted coefficient if not yet available) in LL band. The measure of the based sensitivity threshold in wavelet domain is based on the subjective test in [1]. An image with the background intensity set to 127 is created, uniformly distributed random noise of known energy is added to the coefficients of center region of each subband in turn. The based sensitivity threshold of each subband is determined as the increasingly added energy level of random noise can be just noticeable. Fig. 4 shows the based sensitivity threshold of each subband. However, by Weber's law, this threshold is varies with the background intensity. The luminance masking adjustment used in [3] is adopted and shown in Fig. 5.

The contrast masking means the fact that the reduction in visual sensitivity of stimuli which is caused by the increasing spatial nonuniformity of the background

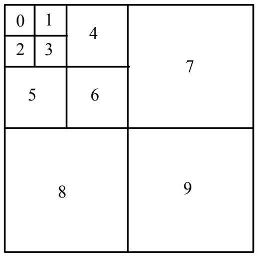


Fig. 3 Band number scheme for 3-level wavelet

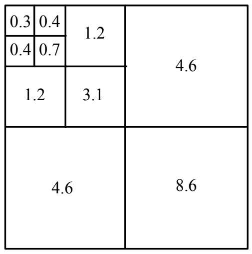


Fig. 4 Based sensitivity threshold of each subband

luminance. In transformed domain, it can be given by exploiting the information of inter-band and the intra-band masking adjustment [3]. By taking account of the varying sensitivity of each subband, it is reasonable to simplify the masking effect by using the largest pyramid coefficient weighted by modulation transfer function (MTF). Therefore, the contrast masking adjustment can be described as

$$m_{\mathrm{Y},C}(b,x,y)=\begin{cases}1.0 & ,b=0\\ \max\left\{1.0, f(\hat{r}_{\mathrm{Y}},\omega_{\mathrm{Y}})^{\varphi}\right\} & ,b\neq 0\end{cases}$$
$$f(\hat{r}_{\mathrm{Y}},\omega_{\mathrm{Y},MTF})=\max_{1\le n\le b}(\hat{r}_{\mathrm{Y}}^{2}(n,i,j)\cdot\omega_{\mathrm{Y}}(n)) \tag{3}$$
$$\text{for } i=\left\lfloor\frac{x}{p}\right\rfloor, j=\left\lfloor\frac{y}{p}\right\rfloor, p=2^{(\lceil b/3\rceil-\lceil n/3\rceil)}$$

where $\omega_{\mathrm{Y}}(n)$ is the energy weight for the n-th band and defined as the normalized spatial-frequency desensitivity according to the MTF curve [2], and $\varphi=0.035$.

3.2 Chrominance detection threshold measure

It is known that the coefficients matrix of LL band (b=0) may be viewed as the lower resolution image of the original image. That is, there only exists small difference between LL band image and original image in both intensity and gradient, besides resolution. These LL band coefficient matrices of luminance and chrominance components preserve the properties inherent in spatial domain.

Let **k** be the LL band target coefficient ($\hat{r}_{\mathrm{Y}}(0,x,y)$, $\hat{r}_{\mathrm{Cb}}(0,x,y)$, $\hat{r}_{\mathrm{Cr}}(0,x,y)$) and the corresponding perceptual redundancy is to be estimated. For simplicity, the notation of tristimulus values is given by ($Y_{\mathbf{k}}$, $Cb_{\mathbf{k}}$, $Cr_{\mathbf{k}}$) and the corresponding adjusted sensitivity threshold $t_{\mathrm{Y},D}(0,x,y)$ is assigned to $t^{\mathbf{k}}_{\mathrm{Y},D}$. To find color samples located on the JNCD surface and satisfy the constrain mentioned above, color $\mathbf{k}=(\mathrm{Y}_{\mathbf{k}},\mathrm{Cb}_{\mathbf{k}},\mathrm{Cr}_{\mathbf{k}})$ and the following noise contaminated pixels

$$\mathbf{k}_1=(\mathrm{Y}_{\mathbf{k}}+t^{\mathbf{k}}_{\mathrm{Y},D},\mathrm{Cb}_{\mathbf{k}},\mathrm{Cr}_{\mathbf{k}}) \tag{4}$$
$$\mathbf{k}_2=(\mathrm{Y}_{\mathbf{k}}-t^{\mathbf{k}}_{\mathrm{Y},D},\mathrm{Cb}_{\mathbf{k}},\mathrm{Cr}_{\mathbf{k}}) \tag{5}$$

are needed to transform to *CIELAB* color space. The corresponding transformed colors are given by $\tilde{\mathbf{k}}$, $\tilde{\mathbf{k}}_1$, $\tilde{\mathbf{k}}_2$, respectively.

In *CIELAB*, the colors spread on the surface of JNCD sphere around the target color are expressed by a color set.

$$\mathbf{S}_{\tilde{\mathbf{k}}}=\{\tilde{\mathbf{s}}_{\mathrm{i}}\mid \|\tilde{\mathbf{s}}_{\mathrm{i}}-\tilde{\mathbf{k}}\|=JNCD\} \tag{6}$$

where $\|\cdot\|$ means the Euclidean distance. We address on two color subsets of $\mathbf{S}_{\tilde{\mathbf{k}}}$, in which colors contaminated with luminant detection threshold have been considered.

$$\mathbf{C}_{\tilde{\mathbf{k}}_1}=\{\tilde{\mathbf{c}}_{\mathrm{j}}\mid\tilde{\mathbf{c}}_{\mathrm{j}}\in\mathbf{S}_{\tilde{\mathbf{k}}},\ |L_{\tilde{\mathbf{c}}_{\mathrm{j}}}-L_{\tilde{\mathbf{k}}}|=D_1\} \tag{7}$$
$$\mathbf{C}_{\tilde{\mathbf{k}}_2}=\{\tilde{\mathbf{c}}_{\mathrm{k}}\mid\tilde{\mathbf{c}}_{\mathrm{k}}\in\mathbf{S}_{\tilde{\mathbf{k}}},\ |L_{\tilde{\mathbf{c}}_{\mathrm{k}}}-L_{\tilde{\mathbf{k}}}|=D_2\} \tag{8}$$

where $D_1=\|\tilde{\mathbf{k}}_1-\tilde{\mathbf{k}}\|$ and $D_2=\|\tilde{\mathbf{k}}_2-\tilde{\mathbf{k}}\|$. In our model, there are 16 color samples, $\tilde{\mathbf{p}}_1$, $\tilde{\mathbf{p}}_2$ …, and $\tilde{\mathbf{p}}_{16}$, are chosen from these two subsets for color mapping. Color samples $\tilde{\mathbf{p}}_1$, $\tilde{\mathbf{p}}_2$ …, and $\tilde{\mathbf{p}}_{16}$ are transformed back to the *YCbCr* and given by $\mathbf{p}_1$, $\mathbf{p}_2$ …, and $\mathbf{p}_{16}$, respectively. The perceptually indistinguishable region of color **k** can be approximately approached by these mapping colors. Finally, the estimated adjusted sensitivity threshold of color **k** for *Cb* and *Cr* channels can be conservatively obtained by taking the minimal distance between color **k** and the mapping colors along *Cb* and *Cr* channel.

$$t^{\mathbf{k}}_{\mathrm{Cb},D}=\min_{i=1\text{ to }16}\left|\mathrm{Cb}_{\mathbf{p}_i}-\mathrm{Cb}_{\mathbf{k}}\right| \tag{9}$$
$$t^{\mathbf{k}}_{\mathrm{Cr},D}=\min_{i=1\text{ to }16}\left|\mathrm{Cr}_{\mathbf{p}_i}-\mathrm{Cr}_{\mathbf{k}}\right| \tag{10}$$

where $(Y_{\mathbf{k}},Cb_{\mathbf{k}},Cr_{\mathbf{k}})$ and $(Y_{\mathbf{p}_i},Cb_{\mathbf{p}_i},Cr_{\mathbf{p}_i})$ are tristmulus values of color **k** and $\mathbf{p}_i$ in *YCbCr*, respectively. That is, $t_{\mathrm{Cb},D}(0,x,y)$ and $t_{\mathrm{Cr},D}(0,x,y)$ are given by $t^{\mathbf{k}}_{\mathrm{Cb},D}$ and $t^{\mathbf{k}}_{\mathrm{Cr},D}$.

Since the luminance CSF is significantly higher than the chromatic CSFs, the based sensitivity threshold dominated by luminance component can be reasonably applied to chrominance component.

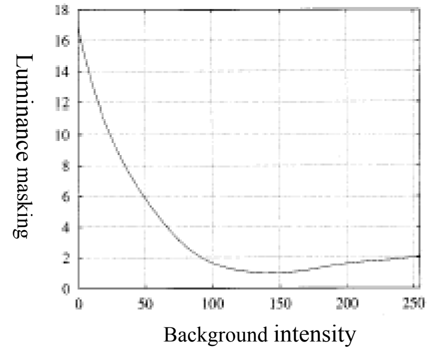
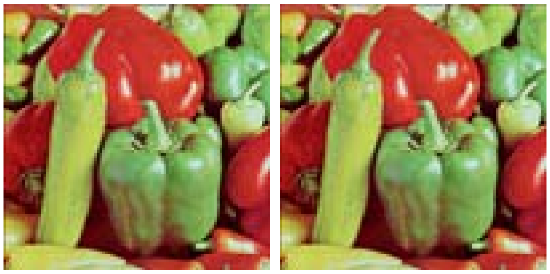


Fig. 5 Luminance masking due to background intensity.



(a) (b)

Fig. 6 (a) Original "Pepper" (b) JND contaminated version

$$\hat{t}_{\mathrm{Cb},JND}(b,x,y) = t_{\mathrm{Cb},D}(0,x,y)\cdot\frac{t_{base}(b)}{t_{base}(0)}\cdot m_{\mathrm{Cb},C}(b,x,y) \quad (11)$$

$$\hat{t}_{\mathrm{Cr},JND}(b,x,y) = t_{\mathrm{Cr},D}(0,x,y)\cdot\frac{t_{base}(b)}{t_{base}(0)}\cdot m_{\mathrm{Cr},C}(b,x,y) \quad (12)$$

$m_{\mathrm{Cb},C}(b,x,y)$ and $m_{\mathrm{Cr},C}(b,x,y)$ are derived by modifying Eq. (3) in the sense that $\omega_{\mathrm{Cb}}(n)$ and $\omega_{\mathrm{Cr}}(n)$ are evaluated according to the corrected MTF curve fit to chrominance components and φ is substituted by 0.125. Eventually, the adaptive quantizer step sizes are evaluated as follows.

$$s_{\mathrm{Y}}(b,x,y) = 2\sqrt{3}\,\hat{t}_{\mathrm{Y},JND}(b,x,y) \quad (13)$$

$$s_{\mathrm{Cb}}(b,x,y) = 2\sqrt{6}\,\hat{t}_{\mathrm{Cb},JND}(b,x,y) \quad (14)$$

$$s_{\mathrm{Cr}}(b,x,y) = 2\sqrt{6}\,\hat{t}_{\mathrm{Cr},JND}(b,x,y) \quad (15)$$

4. SIMULATION RESULTS

The compression results is performed by testing 512×512 images with color depth of 24 bits. To show the color model works, a subjective test that compares the perceptual quality of the image contaminated by noises of JND profiles with that of the original image is shown in Fig. 6. The contaminated image is obtained by adding to or subtracting from three color components of original coefficient with its corresponding JND values. The JND contaminated version with 31.9dB in PSNR has the same perceptual quality as the original image at a viewing distance of about 6 times the image height.

The entropies of three color components obtained by using proposed coefficient-wise quantizer are compared with that obtained by using band-wise quantizer [6]. In [6], Watson *et al*. use two-alternative forced choice procedure to measure the visual detection thresholds for samples of uniform DWT quantization noise in Y, Cb, and Cr channels and provide a simple band variance to adjust the band quantization factor. The compression results enaluated by first order entropies are shown in Table 1. The perceptual quality of both reconstructed color images is transparent at the same viewing condition mentioned above. It can be shown that the compression efficiency using proposed adaptively color quantizer outperforms that using Watson's band-wise quantizer in not only luminance component but also chrominance components. This indicates that the proposed color visual model effectually quantifies the perceptual redundancy in the form of error visibility thresholds, which can be successfully exploited to tune the color quantization stage of the compression scheme.

Table 1. Entropies for band-wise quantization and the proposed coefficiet-wise quantization

Image	Entropy		Compression Gain
	Watson band-wise quantization	Proposed coefficiet-wise quantization	
Pepper	Y:1.03 Cb:0.14 Cr:0.32	Y:0.63 Cb:0.07 Cr:0.24	39% 18% 25%
F16	Y:1.19 Cb:0.11 Cr:0.13	Y:0.76 Cb:0.08 Cr:0.10	41% 27% 23%
Baboon	Y:2.04 Cb:0.17 Cr:0.35	Y:1.13 Cb:0.13 Cr:0.29	44% 23% 17%
Lena	Y:0.97 Cb:0.13 Cr:0.26	Y:0.51 Cb:0.11 Cr:0.21	47% 15% 19%

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