PREDICTION ERROR PREPROCESSING FOR COLOR IMAGE COMPRESSION

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ABSTRACT

In this paper, a prediction error preprocessor based on the just noticeable distortion (JND) for the color image compression scheme is presented. The variance of prediction error signals we can reduce, the less objective distortion of the reconstructed image we can achieve at a given bit rate or the lower bit rate of the reconstructed image we can obtain at the same visual quality. Since the human visual perception to color visual signals has a limited sensitivity, any change below the visibility threshold cannot be detected by human eyes. We therefore use a new color JND estimator that is incorporated into the design of the prediction error preprocessor in the color image compression scheme. Without introducing the perceptual distortion into prediction error signals, the dynamic range of prediction error signals for coefficients in each color component of the color image is reduced to increase the compression performance. The estimated JND is also incorporated into the design of the quantization stage in the color image compression scheme. In the simulation results, the bit rate required by the compression scheme with the prediction error preprocessor is lower than that without the prediction error preprocessor at the consistent visual quality of the reconstructed color image.

1. INTRODUCTION

In the research efforts of perceptual image coding, the coding distortion is properly distributed and shaped with less objective distortion. This can be achieved while the JND profile of the image is accurately measured and applied to the coding scheme. In [1], the JND threshold for each coefficient in a given subband is measured by combining band sensitivities, background luminance, and texture masking to set the quantization level in a differential pulse code modulation (DPCM) quantizer. In [2], a mathematical model for estimating the base JND threshold in the wavelet domain is designed to construct the perceptually lossless quantization matric. In [3], the masking thresholds derived in a locally adaptive fashion based on subband decomposition are applied to the design of a locally adaptive perceptual quantization scheme for achieving high performance in terms of quality and bit rate. In [4], a new JND estimator for video is devised in image-domain with the nonlinear additivity model for masking and is incorporated into a motion-compensated residue signal preprocessor for variance reduction toward coding quality enhancement. Tang [5] further investigated perceptual video coding by incorporating the motion attention model, visual sensitivity model, and visual masking model for the purpose of adaptive quantization. In [6], the sensitivity of the HVS to edges is considered to construct a classified vector quantization method for image compression. Nevertheless, few research efforts [7]-[12] aim at the perceptual compression schemes that are designed for color images.

In this paper, a prediction error preprocessor based on the JND is investigated for higher performance in the design of the color image compression scheme. The wavelet-domain JND of each coefficient in luminance and chrominance components of color images are estimated in a locally adaptive fashion based on the wavelet decomposition. The preprocessor is then designed by adjusting an appropriate quantity regulated by the JND profiles to shape the prediction error signals such that the perceptual distortion of the reconstructed color image can be reduced. Furthermore, for any standard color image coder, the proposed preprocessor can be also used to preprocess the input color image of the coder such that the processed signal has smaller variance resulting in less objective distortion of the reconstructed color image for a given bit rate.

2. MEASURE OF SUBBAND JND PROFILES FOR COLOR IMAGES

Measurement of the receptive fields shows that the multichannel frequency- and orientation-selective components demonstrate approximately a dyadic structure. The measurement can be approached by the dyadic structure of the pyramid wavelet transformation that decomposes the input image into subbands that have different levels and orientations. The subband differs from each other in terms of its sensitivity and visual masking properties. By using such characteristics, the wavelet-domain JND of each efficient in luminance (Y) and chrominance (C_b and C_r) components of color images can be estimated in a locally adaptive fashion based on the wavelet decomposition. The estimated JND of the wavelet coefficient at location (i, j) in the subband with transform level λ and orientation θ of color component O in the color image is represented

$$d_O(\lambda, \theta, i, j) = d_{O,D}(\lambda, \theta, i, j) \cdot a_O(\lambda, \theta, i, j) \quad \text{for } O = \mathrm{Y}, \mathrm{C_b}, \mathrm{C_r} \tag{1}$$

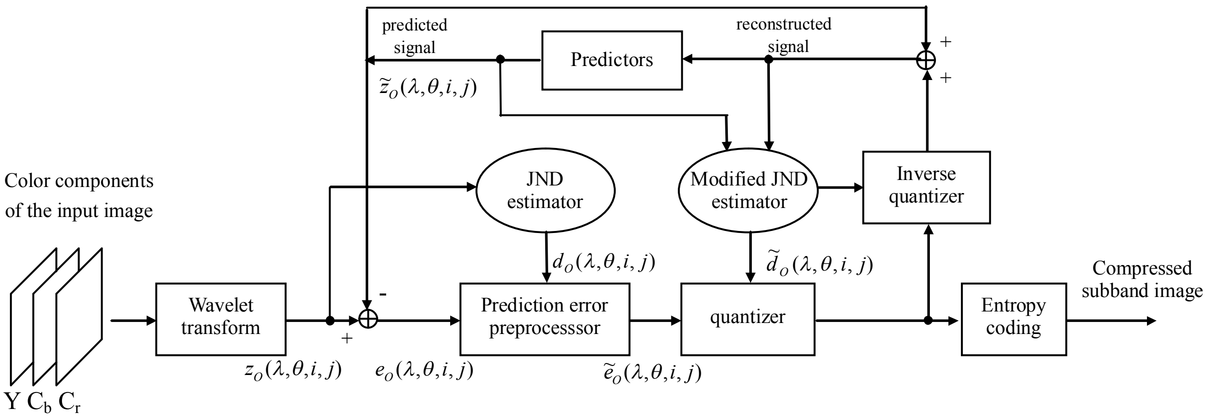


Fig. 1 Block diagram of the proposed perceptual compression scheme.

where $d_{O,D}(\lambda, \theta, i, j)$ is the luminance-adapted base detection threshold and $a_O(\lambda, \theta, i, j)$ is the visual masking adjustment.

Luminance-adapted Base Detection Threshold, $d_{O,D}(\lambda, \theta, i, j)$: The threshold is measured for signals presented against a specified uniform luminance background. The intensity-based contrast sensitivity model proposed in [1], [3] is adopted here. The mathematical model used to measure the base detection threshold for each subband (λ, θ) in O color component can be found in [2]. The contrast sensitivity is measured while a however uniform background intensity level is fixed. The base detection threshold for each subband of four-level 9/7 DWT can be found. It is easily found that the base sensitivity threshold is lowest for the lowest frequency band while higher frequency bands have higher thresholds. In fact, the detection threshold actually varies with the background intensity. This is so-called luminance adaptation. It denotes the variations in the sensitivity depend on the local mean of luminance component in color images. That is, the variations in local mean luminance within the color image will result in substantial variations in wavelet thresholds. In this paper, the luminance adaptation factor is given by the power function proposed in [13].

Visual Masking Adjustment, $a_O(\lambda, \theta, i, j)$: This adjustment is a measure used to increase the detection threshold while taking visual masking effects into account. For luminance component, the contrast masking effect means that the visual sensitivity of stimuli is reduced by the increasing spatial non-uniformity of the background luminance. For chrominance components, the masking also affects the sensitivity to the chrominance components of a target color pixel. We apply the idea proposed in [2] to chrominance components of color images to simplify the estimation of the chromatic JND that is related to the complex features of the HVS. In this paper, the visual masking adjustments proposed in [14] are adopted. The adjustments that have been successfully applied to the watermarking scheme are adopted. The visual masking adjustment for chrominance components is therefore defined by computing a measure of variance within the local region of a target coefficient that is scaled by the visibility of the coefficient.

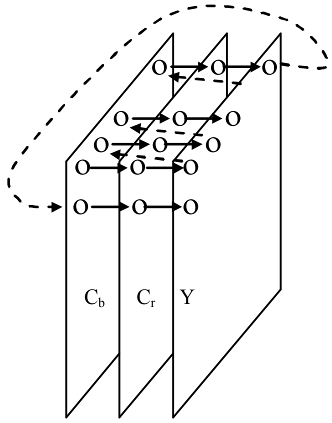
3. PERCEPTUAL COLOR IMAGE COMPRESSION SCHEME

The functional block diagram of the proposed perceptual compression scheme for color images in the wavelet domain is given in Fig. 1, where $z_O(\lambda, \theta, i, j)$, $\tilde{z}_O(\lambda,\theta,i,j)$, $e_O(\lambda, \theta, i, j)$, $\tilde{e}_O(\lambda,\theta,i,j)$, and $d_O(\lambda, \theta, i, j)$, respectively, denote the original current wavelet coefficient, the predicted coefficient, the prediction error before the preprocessing, the prediction error after the preprocessing, and the JND value for the coefficient located at (i, j) of the (λ, θ) subband in the O color component of the color image. The subband JND profiles of the input color image obtained by using the JND estimator presented in Section II are incorporated into the proposed prediction error preprocessor to shape the prediction error and decide the reconstruction level for achieving the increased performance in terms of bit rate at a specified visual quality.

As shown in Fig. 1, the prediction error is obtained by the difference between the current signal and its predicted signal and is given as

$$e_O(\lambda, \theta, i, j) = z_O(\lambda, \theta, i, j) - \tilde{z}_O(\lambda,\theta,i,j) \quad \text{for } O = \mathrm{Y}, C_b, C_r \tag{2}$$

$$\tilde{e}_O(\lambda,\theta,i,j) = \begin{cases} e_O(\lambda,\theta,i,j) + \gamma_O \cdot d_O(\lambda,\theta,i,j), & \text{if } e_O(\lambda,\theta,i,j) < -\gamma_O \cdot d_O(\lambda,\theta,i,j) \\ e_O(\lambda,\theta,i,j) - \gamma_O \cdot d_O(\lambda,\theta,i,j), & \text{else if } e_O(\lambda,\theta,i,j) > \gamma_O \cdot d_O(\lambda,\theta,i,j) \\ e_O(\lambda,\theta,i,j), & \text{otherwise} \end{cases} \tag{3}$$



(b)

Fig. 2 row-wise scanning in the order of C_b, C_r, and Y components for coefficients in each subband. (Symbol "o" means the transform coefficient)

In order to shape the prediction error for higher performance, the prediction error preprocessor utilizes the JND profiles to process the prediction error signals such that the dynamic range of processed prediction error signals can be reduced to achieve lower bit rate or better reconstructed image quality. Each prediction error signal is adjusted by the preprocessor and is shown as Eq.(3), where γ_O is the parameter used to make a trade-off between the visual quality and the coding bit rate of the reconstructed color image for the color component O. The constraint of $\gamma_O \in [0,1]$ is to avoid introducing the perceptual distortion into prediction errors in the JND-based preprocessor. If the estimated JNDs accurately approximates to the actual JNDs for human eyes, the preprocessor with γ_O=1 can extremely adjusts each prediction error signal of the color image to its critical and just visible bound for human eyes to shape the signals for the highest performance. In this paper, the γ_O value is conservatively used in the experiment. In the stage of quantizing the preprocessed prediction error signal, the proposed compression scheme uses a locally adaptive perceptual quantization method. In order to avoid sending a large amount of side information to the decoder, the idea proposed in [3] is extended to eliminate the need for transmitting side information for each step size of each coefficient in each subband of the color image by estimating the available masking from the already received data and a prediction of the transform coefficient to be quantized. This is illustrated by the modified JND estimator shown in Fig. 1. In order to carry out the synchronization of achieving the estimate JND profiles at the coder and the decoder in the proposed compression scheme, the design of the scanning order for subband coefficients is needed. The subbands are scanned from the highest subband to the lowest subband in each color component. In each subband, the coefficients are scanned row-wise in the order of C_b, C_r, and Y components (Fig. 2). The quantization step sizes for each coefficient in subbands of the Y, C_b, and C_r components are thus given by

$$\Delta_O(\lambda,\theta,i,j) = 2\varphi_O \cdot \tilde{d}_O(\lambda,\theta,i,j) \qquad (4)$$

where φ_O is the step size multiplier whose value can be chosen such that the compression distortion is uniformly distributed over the reconstructed image while a tight entropy (bit-rate) budget is required. In this paper, φ_Y=1.0, φ_{Cb}=1.0, and φ_{Cr}=1.0 are used to achieve the perceptually lossless visual quality of the reconstructed image for the variable uniform mid-riser quantizer in the proposed compression scheme.

4. SIMULATION RESULTS

Since the compression performance achieved by the proposed prediction error preprocessor is emphasized, the stage of entropy coding is not further discussed in this paper. In the simulation, the proposed compression scheme therefore makes use of entropies rather than bit rates to represent its performance while a specified visual quality of the reconstructed color image is obtained. Meanwhile, the subjective viewing tests based on the perceived quality have been conducted in the simulation. In each viewing test, the pair images are displayed side by side on the screen of the monitor for evaluating the perceptual difference between the two images. The presentation order of the image pairs is randomized to obtain a fair evaluation.

In this paper, we assume that half of the reconstruction error of each signal is induced by the quantization error of the perceptual quantizer and the other is induced by the prediction error from the preprocessed signals. We use a simple condition to restrict both parts of the reconstruction error of the signal within half of its visibility threshold such that the overall reconstruction error is under the JND value. That is, the condition γ_O=0.4 and φ_O=0.5 is used in the simulation. The conservative constraint of γ_O=0.4 (instead of γ_O=0.5) is adopted because of the description in Section 3. To clarify the performance of the proposed prediction error preprocessor for a variety of color images, Table I compares the entropies obtained using the proposed compression scheme with γ_O=0.4 and φ_O=0.5 with those obtained using proposed compression scheme γ_O=0 and φ_O=1.0 at nearly a perceptually lossless quality. The proposed compression scheme with γ_O=0 and φ_O=1.0 means that prediction error preprocessor is not applied to the prediction error signals in each subband of three color components. That is, the performance of the reconstructed color image is obtained by using only the perceptual quaizer which restrict the quantization error within the corresponding JND threshold. The results show that entropies of the reconstructed image are lower at nearly the same perceived quality when the variance of prediction error signals is effectively reduced by the prediction error preprocessor. One can see that the proposed prediction error preprocessor indeed improves the performance of the proposed compression scheme while the prediction error preprocessor is applied to the compression scheme. Meanwhile, the proposed compression scheme is also compared with the existing Watson's method proposed in [2]. In [2], the mathematical model is proposed to measure the base detection

Table I Entropies of the proposed compression scheme with preprocessor, without preprocessor and the Watson's compression method at nearly a perceptually lossless quality of the reconstructed color images. (G_1: gain of the proposed scheme with γ_O=0, φ_O=1.0; G_2: gain of the proposed scheme with γ_O=0.4, φ_O=0.5)

Image	Entropy			Gain	
	Watson's method	Proposed scheme (γ_O=0, φ_O=1.0)	Proposed scheme (γ_O=0.4, φ_O=0.5)	G_1	G_2
Baboon	1.296	1.089	1.035	15.98%	20.09%
Barbara	0.697	0.637	0.621	8.65%	10.99%
Goldhill	0.775	0.752	0.738	3.05%	4.77%
Leaf	0.575	0.491	0.465	14.55%	19.13%
Lena	0.542	0.510	0.495	5.90%	8.79%
Monarch	0.565	0.512	0.489	9.49%	13.44%
Sail	0.863	0.739	0.717	14.36%	16.91%

threshold for each subband (λ, θ) in O color component and is utilized to design a simple perceptually lossless quantization matrix for compressing color images . Table I lists the overall entropy comparison of the color images under test, between the Watson's method and the proposed compression scheme. It can be seen that entropies are improved with the proposed scheme.

5. CONCLUSIONS

A prediction error preprocessor is presented with the goal to reduce the dynamic range of the prediction error signals of the color image to be compressed. The lower bit rate of the reconstructed image can be obtained by using the preprocessor while reaching high visual quality. For this purpose, a color JND estimator that takes into account various masking effects of human visual perception is proposed and incorporated into the preprocessor for the design of the perceptual color image compression scheme using the DPCM technique. The proposed compression scheme with the preprocessor generates consistent quality images at a lower entropy when comparing with that without prediction error preprocessor and the existing compression method. In the future work, the preprocessor will be compliantly applied to the JPEG and JPEG2000 coders in order to achieve higher performance in terms of bit rate at the same visual quality.

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