MULTIPLE DESCRIPTION CODING BASED ON PHASE SCRAMBLING WITH ADJUSTABLE SPREAD RANGE

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ABSTRACT

This paper describes a multiple description coding (MDC) of images, introducing a phase scrambling with the adjustable dispersion extent of sample value. Whereas a phase scrambling gains robustness to transmission errors, it loses the time-localized information. Consequently, when this phase scrambling process is combined with a wavelet-based coder for the MDC, its objective coding performance is largely dependent on the spread range of phase scrambling. In this paper, we propose a novel MDC using phase scrambling with the variable spread capability of the pixel value. For the control of the spread range, our design of the phase scrambling is based on the group delay response, instead of the phase response. Furthermore, we modify a quadtree-based wavelet coder according to the spread range for the proposed MDC with our phase scrambler. Simulation results show the usefulness of the proposed technique.

1. INTRODUCTION

In recent years, there has been much interest in transmission of compressed images and video over noisy channels [1]–[8]. Since cells in packet-switched networks, such as the current Internet, can be lost due to network congestion and buffer overflow, it is one of significant challenges to make the source coders error-resilient and network-adaptive for providing satisfactory visual quality. Multiple description coding (MDC) [1] is one efficient technique to protect data from packet losses, where a single information source is divided into several coded substreams and the resulting descriptions are independently transmitted over the network.

Various approaches to generate multiple descriptions of an image have been presented [1]. The simplest method is to first partition the source data into several sets and then compress each of them. In [2], Jayant proposed a separation of odd- and even-numbered samples for a speech signal. At the decoder, interpolation process is employed to reduce the effect of lost descriptions. This approach can be an effective solution to robust transmission of images. However, it relies only on the redundancy in the original signal. Other MDC schemes introduce redundancy in different ways: through multiple quantizers, correlating transforms or lapped orthogonal transforms (LOTs) [3]–[6]. Recently, the MDC based on phase scrambling has been proposed in [7], where an input image is passed through a cyclic allpass filter for reducing the perceptual effect of transmission errors. Note that the terms “phase scrambling” and “cyclic allpass filtering” are used interchangeably in this paper. Compared with the MDC based on the LOT [6], the MDC using phase scrambling and wavelet-based coder is shown to yield excellent reconstructed image quality at low bit rates. However, since the phase scrambling in [7] spreads each pixel value all over the image samples irrespective of error rates, this MDC scheme with wavelet-based coder leads to a significant degradation of the objective coding performance.

In this paper, we present a generalized MDC with phase scrambling, where the distribution of the spread is controlled via a simple parameter. Phase scrambling is implemented by adding some randomized phase spectrum to that of the input source. Therefore, we can control the spread range of each sample by designing the phase scrambling via the group delay response. As a result, adequate phase scrambling for the MDC can be selected based on channel loss, desired reconstruction performance and desired compression. Moreover, we improve the partitioning process in a quadtree-based wavelet coder depending on the spread extent of the phase scrambler. Finally, simulation results are shown to demonstrate the validity of the proposed approach.

2. THE MDC BASED ON PHASE SCRAMBLING

A block diagram of the MDC with phase scrambling [7] is depicted in Fig. 1. Here an input image is passed through a cyclic allpass filter in order to increase robustness over the loss of packets. The resulting image is then partitioned into several bit-streams by odd/even separation, and encoded to be multiple descriptions through embedded wavelet coder. At the decoder, the transmitted image is reconstructed using the inverse cyclic allpass filter, after lost descriptions are replaced with averages of their available neighbors. Hereafter, we consider the MDC of $L \times L$ images with four channels for simplicity.

The frequency response of a cyclic filter $h(n)$ with time-argument interpreted modulo L is defined as the L-point DFT of the impulse response

$$H(k) = \sum_{n=0}^{L-1} h(n) W_L^{kn} \quad \text{for} \quad k = 0, 1, \ldots, L-1, \tag{1}$$

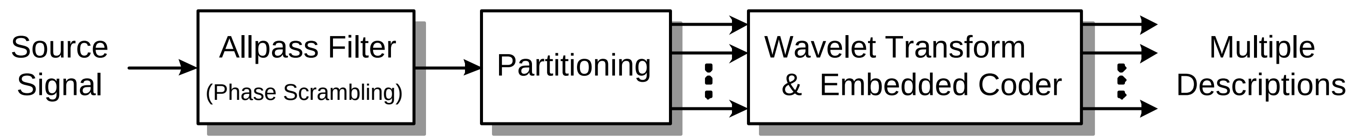


Figure 1: Framework of the MDC with phase scrambling for low bit rates (The number of descriptions in this paper is four).

where $W_L = e^{-j2\pi/L}$ [9]. This is equivalent to sampling the typical frequency response $\sum_{n=0}^{L-1} h(n)e^{-j\omega n}$ at L discrete values of the frequency $\omega_k = e^{j2\pi k/L}$. For a simple L-cyclic allpass filter $A(k) = e^{j\phi(k)}$, the $L \times L$ circular matrix $\mathbf{A}$ formed from the impulse response $a(n)$ of the cyclic allpass filter is given as [9]

$$\mathbf{A} = \begin{bmatrix} a(0) & a(1) & \cdots & a(L-1) \\ a(L-1) & a(0) & \cdots & a(L-2) \\ \vdots & \vdots & \ddots & \vdots \\ a(1) & a(2) & \cdots & a(0) \end{bmatrix} \tag{2}$$

$$= \frac{1}{L}\mathbf{W}_L^{\dagger}\Lambda\mathbf{W}_L, \tag{3}$$

where $\mathbf{W}_L$ is the DFT matrix with $[\mathbf{W}_L]_{k,i} = W_L^{ki}$, for $k,i = 0,1,\ldots,L-1$, Λ is a diagonal matrix with elements $A(k)$, i.e., $\Lambda = \mathrm{diag}\left\{e^{j\phi(0)}, e^{j\phi(1)}, \ldots, e^{j\phi(L-1)}\right\}$, and the superscript † stands for the transpose conjugate. The cyclic allpass filter $a(n)$, therefore, has the input-output relation in the matrix form:

$$\mathbf{x}_{ps}^T = \mathbf{A}\mathbf{x}^T = \frac{1}{L}\mathbf{W}_L^{\dagger}\Lambda\mathbf{W}_L\mathbf{x}^T, \tag{4}$$

where $\mathbf{x}$ and $\mathbf{x}_{ps}$ are the input and output vectors for the input signal $x(n)$ and output signal $x_{ps}(n)$, respectively,

$$\mathbf{x} = \left[\, x(n) \;\; x(n-1) \;\; \cdots \;\; x(n-L+1) \,\right] \tag{5}$$

$$\mathbf{x}_{ps} = \left[\, x_{ps}(n) \;\; x_{ps}(n-1) \;\; \cdots \;\; x_{ps}(n-L+1) \,\right]. \tag{6}$$

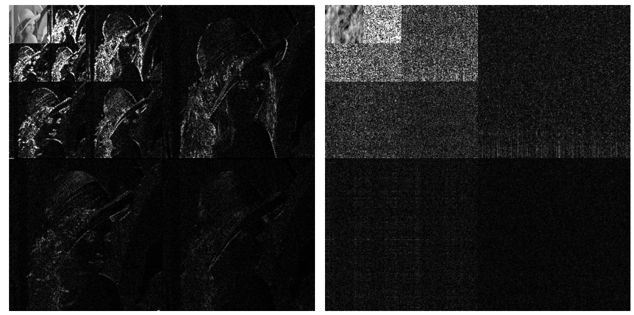
In [7], this allpass filtering based on the DFT is referred to as phase scrambling, because it affects the only phase of the frequency response. For a real input signal $x(n)$, the condition such that the scrambled signal $x_{ps}(n)$ will be also real is that the phase spectrum $\phi(k)$ is an odd-symmetry function [7], [8].

The inverse process of phase scrambling is then expressed as

$$\hat{\mathbf{x}}^T = \mathbf{A}^{-1}\hat{\mathbf{x}}_{ps}^T = \frac{1}{L}\mathbf{W}_L^{\dagger}\Lambda^{\dagger}\mathbf{W}_L\hat{\mathbf{x}}_{ps}^T \tag{7}$$

$$\Lambda^{\dagger} = \mathrm{diag}\left\{e^{-j\phi(0)}, e^{-j\phi(1)}, \ldots, e^{-j\phi(L-1)}\right\}, \tag{8}$$

where $\hat{\mathbf{x}}_{ps}$ and $\hat{\mathbf{x}}$ are the input and output vectors, defined similar to (5) and (6), respectively. Hence, these allpass filtering processes, or phase scrambler/unscrambler, can be efficiently implemented by the L-point (inverse) fast Fourier transform.



(a) (b)

Figure 2: Three-levels wavelet transforms. (a) Original Lena image. (b) Scrambled Lena image.

3. PROPOSED MDC SCHEME

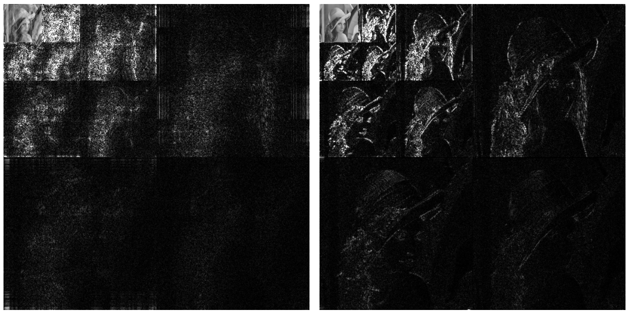
3.1 Phase scrambling design based on the group delay

Subband coding technique can be utilized for the scrambled image, since the phase scrambling does not change the magnitude response [7]. However, embedded wavelet coders, such as EZW [10], SPIHT [11] and SPECK [12], don't work well for the fully scrambled image. Because the phase scrambling with a random $\phi(k)$ [7], [8] completely alter the phase spectrum. Fig. 2 shows the transformed images of the 512×512 Lena image and its scrambled image ($L = 512$), where the wavelet transform with the 9/7 Daubechies filter [13] is employed for each image and the high-frequency bands have been enhanced to show detail. Note that the information on discontinuities or edges in the wavelet-domain of Fig. 2(b) is thoroughly dispersed. This significantly reduces the performance of embedded coders. In the following, we consider the control of the spread range in the phase scrambler for adjusting the trade-off between compression performance and reconstruction quality.

To accomplish this, we design the phase scrambling by means of the group delay response, instead of the phase response. The group delay response of the L-cyclic allpass filter can be defined as

$$\tau(k) = -\frac{(\phi(k) - \phi(k-1))}{(2\pi/L)} \tag{9}$$

This group delay $\tau(k)$ indicates a time delay at each discrete frequency $\omega_k = e^{j2\pi k/L}$. Since the input and output signals of this system are cyclic with period L, $\tau(k)$ in (9) is assumed to be $-L/2 \le \tau(k) \le L/2$ without loss of generality. In order to control the spread range of phase scrambling, we restrict



(a) (b)

Figure 3: Three-levels wavelet transforms of scrambled Lena image via the proposed phase scrambling. (a) $d = 1/8$. (b) $d = 1/64$.

on the group delay response $\tau(k)$ as

$$|\tau(k)| \leq \frac{L}{2}d, \quad k = 0, 1, \ldots, L-1 \tag{10}$$

where d is a parameter between 0 and 1. Under this condition in (10), one can, therefore, construct the phase scrambling with the adjustable spread range from the phase response $\phi(k)$:

$$\phi(k) = \begin{cases} 0 \text{ or } \pi, & k = 0 \text{ and } k = \frac{L}{2} \\ \left(\sum_{i=1}^{k} \tau(i)\right) \frac{2\pi}{L} + \phi(0), & k = 1, \ldots, \frac{L}{2} - 1 \\ -\left(\sum_{i=L-k}^{1} \tau(i)\right) \frac{2\pi}{L} - \phi(0), & k = \frac{L}{2} + 1, \ldots, L-1 \end{cases} \tag{11}$$

Herein, $\phi(k)$ has the antisymmetric property for the scrambled image to be a real signal. In this paper, we choose $\phi(0) = \phi(L/2) = 0$ for simplicity. Fig. 3 shows examples of wavelet transform for the scrambled Lena images by our designed allpass filter. It is clear that the proposed design allows the control of spread range using one parameter d in (10).

3.2 Embedded image coder for the proposed MDC

To be suited to the MDC using the proposed phase scrambling, we modify a partitioning process in the quadtree-based coder. In the quadtree-based coder, e.g., SPECK [12], a significant set within each subband is recursively partitioned into the four subsets of quad-size for finding significant transform coefficients. This procedure exploits a high correlation in adjacent wavelet coefficients of an image. However, phase scrambling also spreads this correlation property, as shown in Fig. 3. Assuming that the group delay sequence $\tau(k)$ in (10) is uniformly distributed between $-(L/2)d$ and $(L/2)d$, the standard deviation $D(d)$ of the pixel spread of our phase scrambling is obtained as

$$D(d) = \sqrt{\int_{-\frac{L}{2}d}^{\frac{L}{2}d} x^2 \frac{1}{Ld} \mathrm{d}x} = \frac{Ld}{\sqrt{12}}. \tag{12}$$

Therefore, the standard deviation for the separated four subimages of size $L/2 \times L/2$ in the MDC can be expressed as $D_s(d) = Ld/(2\sqrt{12})$. Hence, in the functions `ProcessS()` and `CodeS()` of the SPECK algorithm, we partition a significant set below the size of $D_s(d)/2^l \times D_s(d)/2^l$ into pixel-level transform coefficients, where l ($l = 1, 2, \cdots$) denotes the level or scale of the wavelet transform for the corresponding set. In the proposed MDC, this modification of the quadtree-based coder reduces the bits for significant testing of sets composed of distributed significant pixels, depending on the spread parameter d.

4. EXPERIMENTAL RESULTS

The compression performance of the MDC with our designed phase scrambling is evaluated through the comparison with the counterpart with the conventional phase scrambling [7]. In all cases, we employ a 5-levels wavelet decomposition with the 9/7 Daubechies filter [13] and the quadtree-based embedded coder SPECK [12] after odd/even separation of the scrambled image in order to generate four descriptions of an input image.

Fig. 4 shows the rate-distortion curves of various phase scrambling processes for the Lena image, when one description and four descriptions are received at the decoder. The PSNR results of image coding without multiple descriptions are also plotted in Fig. 4(b). Thanks to the controlled spread range, the proposed MDC with a lower value of d yields higher PSNRs. On the other hand, Fig. 5 compares the reconstruction performance of the phase scrambling with the spread range $d = 1/8$ and $d = 1/64$ for the Goldhill image. The phase scrambling with wider spread range ($d = 1/8$) provides smoother reconstructed image. In addition, the PSNR values from using the original and modified SPECK in the proposed MDC using phase scrambling with $d = 1/8$ for the Lena image are tabulated in Tables 1 and 2.

5. CONCLUSIONS

In this paper, we presented an efficient MDC based on phase scrambling with the adjustable spread range. The proposed design of phase scrambling is based on the group delay response in consideration of the following wavelet-based coder, and thereby our phase scrambling-based MDC can exchange compression efficiency and perceptual performance depending on error rates. Furthermore, we proposed a novel partitiong algorithm in the quadtree-based coder according to the spread range of transformed coefficients in the wavelet-domain.

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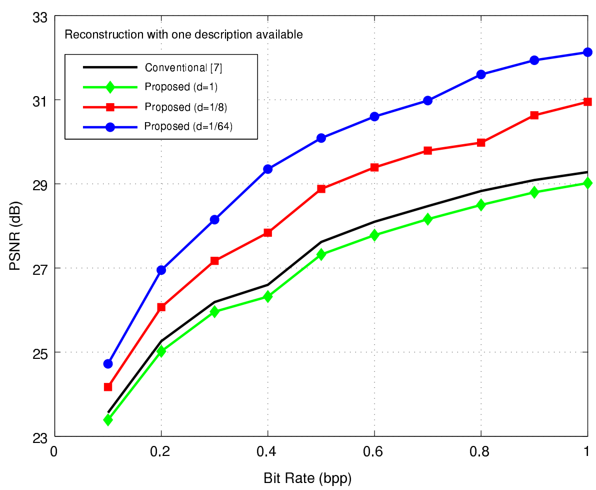
Table 1: Comparison of PSNR results in decibels from available one description

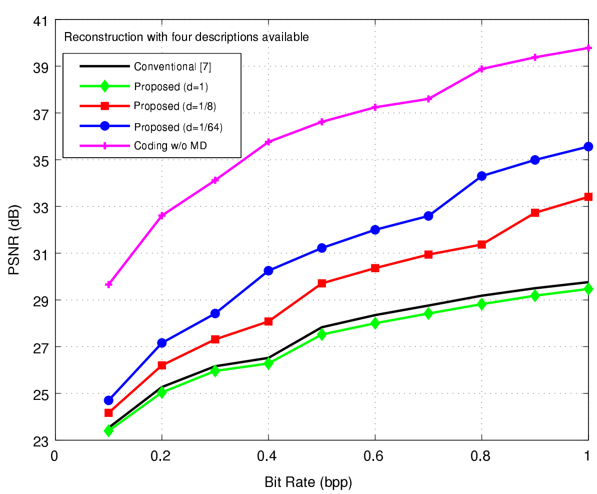
Coder	Bit rate (bpp)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Modified SPECK	24.19	26.17	27.17	27.90	28.92	29.47	29.79	30.01	30.63	30.92
SPECK	24.17	26.06	27.11	27.84	28.88	29.39	29.69	29.97	30.54	30.84

Table 2: Comparison of PSNR results in decibels from available four descriptions

Coder	Bit rate (bpp)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Modified SPECK	24.22	26.26	27.28	28.18	29.73	30.38	30.97	31.37	32.73	33.46
SPECK	24.19	26.19	27.23	28.08	29.70	30.36	30.93	31.33	32.71	33.38



(a)



(b)

Figure 4: Rate-distortion curves via various phase scrambling-based MDC methods with four channels. (a) One description. (b) Four descriptions.

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(a)

(b)

Figure 5: Enlarged portions of reconstructed Goldhill images with one description at 0.5 bpp. (a) $d = 1/8$. (b) $d = 1/64$.

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