All Phase Inverse Discrete Sine Biorthogonal Transform and Its Application in Image Coding

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Abstract —To improve the coding performance in JPEG image compression and reduce the computational complexity, this paper proposes a new transform called All Phase Inverse Discrete Sine Biorthogonal Transform (APIDSBT) based on the All Phase Biorthogonal Transform (APBT) and Inverse Discrete Sine Transform (IDST). Similar to Discrete Sine Transform (DST) matrix and Discrete Cosine Transform (DCT) matrix, it can be used in image compression which transforms the image from spatial domain to frequency domain. Compared with other transforms in JPEG-like image compression algorithm, the Peak Signal-to-Noise Ratio (PSNR) and subjective effects of the reconstructed images using the proposed transform and image coding scheme are better at the same bit rates, especially at low bit rates. The advantage is that the quantization process is simpler and the computational complexity is lower.

Index Terms—Image coding, mathematical transform, Inverse Discrete Sine Transform (IDST), All Phase Biorthogonal Transform (APBT), All Phase Inverse Discrete Sine Biorthogonal Transform (APIDSBT)

I. Introduction

Image is an important source for people to obtain information, and about 70% of the information is obtained through visual system. However, because the data of image and video is huge, it brings great difficulties to the storage, transmission, and processing. Therefore, how to efficiently represent and compress image is one of the key technologies. Moreover, in order to meet people's current requirements for real-time image processing, it is imminent to improve the efficiency and speed of image / video coding. In the 21st century, many international standards for image and video coding have been published and developed one after another, such as JPEG 2000 [1] based on Discrete Wavelet Transform (DWT) and JPEG XR [2] based on Lapped Biorthogonal Transform (LBT) [3]. However, JPEG standard [4] based on Discrete Cosine Transform (DCT) [5], with the advantages of higher performance and lower complexity, is still the most widely used standard for still image compression currently. At the same time, DCT is also the core transform of video compression standards, such as MPEG-2, H.263, MPEG-4, H.264/AVC [6], AVS, and HEVC/H.265 [7]. In H.265, established in 2013, in addition to DCT, the transform module adopts Discrete Sine Transform (DST) for the first time. Nevertheless, in the block based coding standard, serious block effect exists in reconstructed image at low bit rates, and the redundant is still remained among sub-blocks. Furthermore, the quantization table is more complicated, and the quantization step requires more complex multiplications while changing the compression ratio.

To improve the quality of compressed image at low bit rates, Malvar *et al*. proposed the Lapped Orthogonal Transform (LOT) [8] and LBT [3] based on DCT. In the overlapping transform, each block needs to be transformed with a part of the adjacent block after partitioning the image. Therefore, to some extent, the blockiness is reduced. However, ringing effects spread to neighboring blocks and the transform matrix is not square, due to the fact that lapped transform is used.

To solve the above problems, Hou *et al*. designed the All Phase Digital Filter (APDF) [9] and proposed the All Phase Biorthogonal Transform (APBT) [10] based on Walsh-Hadamard Transform (WHT), DCT, and Inverse DCT (IDCT). They derived expression of any order matrix and proposed the JPEG-like image coding algorithm based on APBT. Because APBT has good energy concentration characteristic and high frequency attenuation characteristic, after replacing DCT with APBT in image transform, a simple uniform quantization step can be used to replace the complex quantization table designed by the human visual characteristics in JPEG standard. By this way, the fine quantization is put on low frequencies, whereas the coarse quantization is put on high frequencies. The algorithm is simpler because of the uniform quantization. Experimental results show that the quality of reconstructed image by using APBT for image coding is better than that of conventional DCT. It can effectively reduce blockiness of the reconstructed image, especially at low bit rates. In recent years, the APBT was also applied to color image coding [11] and MPEG video coding [12], [13]. However, APBT is not optimal for image compression, and there is no fast algorithm at present.

To further improve the performance of image coding and reduce the computational complexity simultaneously, this paper proposes a new transform called All Phase

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Inverse Discrete Sine Biorthogonal Transform (APIDSBT) based on APBT and Inverse DST (IDST).

The rest of this paper is organized as follows. Section II investigates the conventional mathematical transforms commonly used in image and video coding. Section III demonstrates the deduction of the new transform and the performance analysis of its basis vectors and basis images. In addition, its application in JPEG-like image coding is described. Experimental results and performance analysis between APIDSBT-JPEG and conventional JPEG algorithms are presented in Section IV. Conclusions and future work are given finally in Section V.

II. Overview of Conventional Mathematical Transforms in Image Coding

In the field of image processing, mathematical transforms and image compression are eternal topics [14]. At present, many conventional mathematical transforms are used in image compression, such as Karhunen–Loève Transform (KLT), Discrete Fourier Transform (DFT), WHT, DCT, DST, DWT, and LBT. Among them, DCT has been widely adopted as the core transform in international standards for image and video compression.

Over the last two decades, to improve the gain and flexibility of image coding, some mathematical transforms for image compression have been put forward. Some transforms have been used to take the place of DCT in JPEG. Although the performance of image compression is improved, yet the complexity of the algorithm is increased. Some representative work is as follows.

In 1995, Shape-Adaptive DCT (SA-DCT) [15] was proposed by Sikora *et al*. and used in image and video coding. Warped DCT (WDCT) [16] was proposed by Cho *et al*. in 2000, which made the frequency distribution of the signal more adapted to the DCT by adjusting filter parameters to crimp frequency of the input signal. In recent years, it has attracted the attention of some scholars [17]. In 2001, Mukundan *et al*. first proposed the Discrete Tchebichef Transform (DTT) [18]. After that, it was developed as an orthogonal transform [19] in 2007. This transform was derived by discrete Tchebichef polynomial kernel and used for image and video compression gradually [20]. In 2015, Oliveira *et al*. proposed the approximate DTT [21] and used it in H.264 scheme. The compression results were slightly better than those of H.264. In 2007, He proposed the Peak Transform (PT) [22] and used it in image compression. The quality of the reconstructed images was improved significantly, but the complexity of the algorithm was increased. In 2008, Zeng *et al*. proposed Directional DCT (D-DCT) [23] and used it in image and video compression. It has a good compression effect on the image in which other directional edges are dominant rather than horizontal or vertical directional edges. In the same year, Guzmán *et al*. proposed the Morphological Transform (MT) [24]. Compared with DCT, the complexity of MT was decreased. However, the performance of image coding was decreased, too. In 2012, Xiong *et al*. proposed the U Transform (UT) [25]. The coding effect of UT in the JPEG scheme is similar to that of DCT, and the computational complexity is basically the same as that of the fast DCT algorithm based on Fast Fourier Transform (FFT). In 2013, inspired by the visual mechanism of human eyes, Asghari *et al*. proposed the Anamorphic Spectrum Transform (AST) [26]. In 2014, Asghari *et al*. further proposed the Discrete Anamorphic Stretch Transform (DAST) [27] and used it in JPEG 2000. The Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity (SSIM) [28] between reconstructed image and original image were improved.

In solving the contradiction between improving the gain of image coding and reducing the complexity of computation, each transform above has its own advantage. It can effectively solve the problem that the complexity of the quantization table and the serious blockiness at low bit rates when DCT is replaced by APBT in JPEG scheme, but there is no fast algorithm for APBT. Despite this, APBT has attracted scholars' wide attention in recent years [29]-[32]. Many transforms based on "all phase" were put forward one after another, and further expanded the transform and its applications. In 2009, Xiong *et al*. constructed the All Phase Biorthogonal U Transform based on 3-degree U system (APBUT3) [29]. In 2010, Guo *et al*. constructed the All Phase Biorthogonal Tchebichef Transform (APBTT) [30] based on discrete Tchebichef system. In 2011, Ma *et al*. applied APBUT3 [31] to color image coding. In 2013, Guo *et al*. constructed two-dimensional interpolation template based on the all phase filter theory and APBUT2 [32] and applied it to image interpolation.

What's more, Jiang *et al*. and Zhang *et al*. proposed the Shape-Adaptive APBT (SA-APBT) [33] and Directional APBT (D-APBT) [34] one after another, and they did a lot of work in MPEG-4 and H.263 video coding [35], [36]. In 2015, the Windowed APBT (WAPBT) [37] was constructed based on the design of windowed APDF. PSNR was adopted as objective assessment to evaluate the quality of reconstructed images with Generalized Pattern Search Algorithm (GPSA) [38], which was used for window sequence optimization. The obtained transform matrix can be used in JPEG-like image coding scheme resulting in better coding performance than DCT and APBT. In 2016, Shan *et al*. proposed the All Phase Discrete Sine Biorthogonal Transform (APDSBT) [39] based on APBT and DST. Applying APDSBT in parallel JPEG-like image coding scheme, the coding performance and computing efficiency were improved significantly.

In summary, the main mathematical transforms commonly used in image and video coding are shown in Fig. 1.

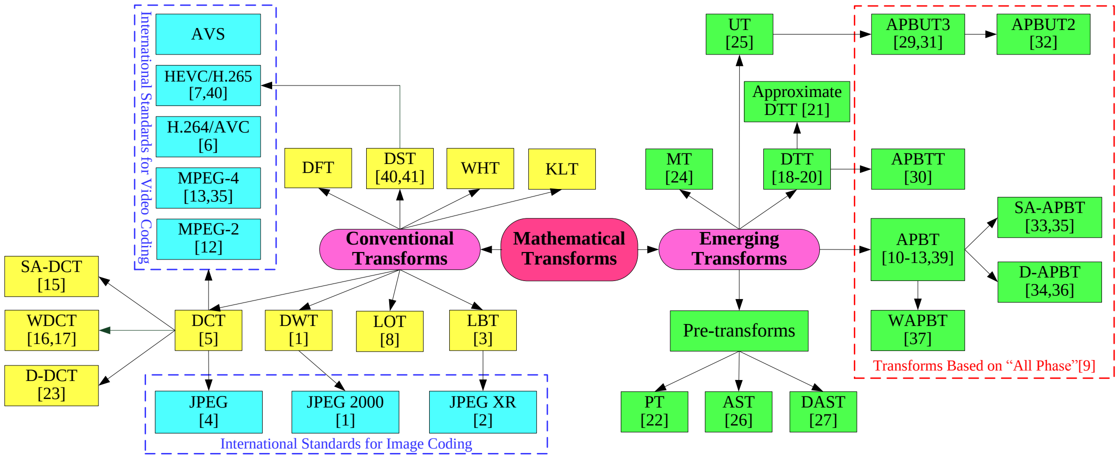


Fig. 1. The main mathematical transforms commonly used in image and video coding.

To better solve the above problems, inspired by the construction process of APBT [10], this paper proposes a new kind of APBT transform by using IDST. In addition, its application in image coding is explored to improve the performance of image coding.

III. All Phase Inverse Discrete Sine Biorthogonal Transform

A. Deduction of APIDSBT

The matrix of DST-VII with size of $N \times N$ is [40], [41]:

$$S(i,j)=\frac{2}{\sqrt{2N+1}}\sin\frac{(2i+1)(j+1)\pi}{2N+1},\ i,j=0,1,\cdots,N-1. \quad (1)$$

Since DST is an orthogonal transform, the inverse DST matrix $\boldsymbol{S}$ is $\boldsymbol{S}^{-1}=\boldsymbol{S}^{\mathrm{T}}$.

According to [10], [37], for a digital sequence $\{x(n)\}$, there are N different values corresponding to the same point $x(n)$. We take the mean of the values as the output of all phase filtering:

$$\begin{aligned} y(n) &= \frac{1}{N}\sum_{i=0}^{N-1} y^{i}(n)=\frac{1}{N}\sum_{i=0}^{N-1}\{\boldsymbol{s}_i^{\mathrm{T}}\{\boldsymbol{S}[\boldsymbol{F}\cdot(\boldsymbol{S}^{-1}\boldsymbol{X}_i)]\}\} \\ &= \frac{1}{N}\sum_{i=0}^{N-1}\{\sum_{k=0}^{N-1}S(i,k)\{F_N(k)[\sum_{j=0}^{N-1}S^{-1}(k,j)x(n-i+j)]\}\} \\ &= \frac{1}{N}\sum_{i=0}^{N-1}[\sum_{j=0}^{N-1}(\sum_{k=0}^{N-1}F_N(k)S(i,k)S^{\mathrm{T}}(k,j))]x(n-i+j) \\ &= \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}[H(i,j)x(n-i+j)], \end{aligned} \quad (2)$$

where

$$\begin{aligned} H(i,j) &= \frac{1}{N}\sum_{m=0}^{N-1}F_N(m)S(i,m)S^{\mathrm{T}}(m,j) \\ &= \frac{1}{N}\sum_{m=0}^{N-1}F_N(m)S(i,m)S(j,m). \end{aligned} \quad (3)$$

Substituting Eq. (3) into Eq. (2), we get:

$$\begin{aligned} y(n) &= \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}[H(i,j)x(n-i+j)] \\ &= \sum_{i=\tau}^{\tau+N-1}\sum_{\tau=-(N-1)}^{N-1}[H(i,i-\tau)x(n-\tau)] \\ &= \sum_{\tau=-(N-1)}^{N-1}[\sum_{i=\tau}^{\tau+N-1}H(i,i-\tau)]x(n-\tau) \\ &= \sum_{\tau=-(N-1)}^{N-1}h(\tau)x(n-\tau)=h(n)*x(n), \end{aligned} \quad (4)$$

where $h(\tau)$ is the unit impulse response of all phase filtering:

$$h(\tau)=\begin{cases}\sum_{i=\tau}^{N-1}H(i,i-\tau), & \tau=0,1,\cdots,N-1, \\ \sum_{i=0}^{\tau+N-1}H(i,i-\tau), & \tau=-1,-2,\cdots,-N+1.\end{cases} \quad (5)$$

According to Eqs. (3) and (5), we get:

$$\begin{aligned} h(\tau) &= \sum_{i=\tau}^{N-1}H(i,i-\tau) \\ &= \sum_{i=\tau}^{N-1}[\frac{1}{N}\sum_{m=0}^{N-1}F_N(m)S(i,m)S(i-\tau,m)] \\ &= \frac{1}{N}\sum_{i=\tau}^{N-1}\sum_{m=0}^{N-1}[F_N(m)S(i,m)S(i-\tau,m)] \\ &= \sum_{m=0}^{N-1}V(\tau,m)F_N(m), \quad \tau=0,1,\cdots,N-1. \end{aligned} \quad (6)$$

Eq. (6) can be expressed in matrix format: $\boldsymbol{h}=\boldsymbol{VF}$, where $\boldsymbol{V}$ connects the unit pulse responses in time domain and sequency response in orthogonal transform domain. We call $\boldsymbol{V}$ the matrix of All Phase Inverse Discrete Sine Biorthogonal Transform (APIDSBT). Similar to DST matrix $\boldsymbol{S}$, it can be used in image compression transforming the image from spatial domain to frequency domain, too. The elements of $\boldsymbol{V}$ can be calculated by:

$$\begin{aligned} V(\tau,m) &= \frac{1}{N}\sum_{i=\tau}^{N-1}S(i,m)S(i-\tau,m) \\ &= \frac{1}{N}\sum_{i=0}^{N-1-\tau}S(i,m)S(i+\tau,m). \end{aligned} \quad (7)$$

After variable substitution: $i \to l,\ \tau \to i,\ m \to j$, Eq. (7) can be rewritten as:

$$V(i,j) = \frac{1}{N}\sum_{l=0}^{N-1-i} S(l,j)S(l+i,j). \tag{8}$$

Substituting Eq. (1) into Eq. (8), the APIDSBT matrix with size of $N \times N$ is obtained, as shown in Eq. (9).

For example, when $N = 8$, the elements of $\boldsymbol{V}$ with size of 8×8 are given in Eq. (10).

B. Performance Analysis of APIDSBT

The transform matrix $\boldsymbol{V}$ can be used for image decomposition while its inverse matrix $\boldsymbol{V}^{-1}$ can be used for image reconstruction. Fig. 2 shows the basis vectors of $\boldsymbol{V}$ and $\boldsymbol{V}^{-1}$ respectively. We can see that the frequency increases with the increase of column number. Besides, the norm of basis vectors in $\boldsymbol{V}$ decreases with the increase of sequency, whereas the norm of basis vectors in $\boldsymbol{V}^{-1}$ increases with the increase of sequency.

$$V(i,j) = \begin{cases} \dfrac{1}{N}, & i = 0,\ j = 0, 1, \cdots, N-1, \\ \dfrac{4}{N(2N+1)} \displaystyle\sum_{l=0}^{N-1-i} \left[\sin\frac{(2l+1)(j+1)\pi}{2N+1} \sin\frac{(2l+2i+1)(j+1)\pi}{2N+1} \right], & i = 1,\ 2, \cdots, N-1,\ j = 0,\ 1, \cdots, N-1. \end{cases} \tag{9}$$

$$\boldsymbol{V} = \begin{bmatrix} 0.1250 & 0.1250 & 0.1250 & 0.1250 & 0.1250 & 0.1250 & 0.1250 & 0.1250 \\ 0.1171 & 0.0943 & 0.0598 & 0.0182 & -0.0248 & -0.0635 & -0.0927 & -0.1083 \\ 0.0971 & 0.0277 & -0.0481 & -0.0925 & -0.0842 & -0.0297 & 0.0407 & 0.0889 \\ 0.0713 & -0.0336 & -0.0817 & -0.0299 & 0.0560 & 0.0767 & 0.0095 & -0.0684 \\ 0.0453 & -0.0616 & -0.0295 & 0.0588 & 0.0345 & -0.0543 & -0.0415 & 0.0484 \\ 0.0237 & -0.0538 & 0.0300 & 0.0302 & -0.0496 & 0.0011 & 0.0488 & -0.0305 \\ 0.0092 & -0.0283 & 0.0386 & -0.0270 & -0.0021 & 0.0296 & -0.0358 & 0.0158 \\ 0.0020 & -0.0072 & 0.0139 & -0.0197 & 0.0226 & -0.0210 & 0.0149 & -0.0054 \end{bmatrix}. \tag{10}$$

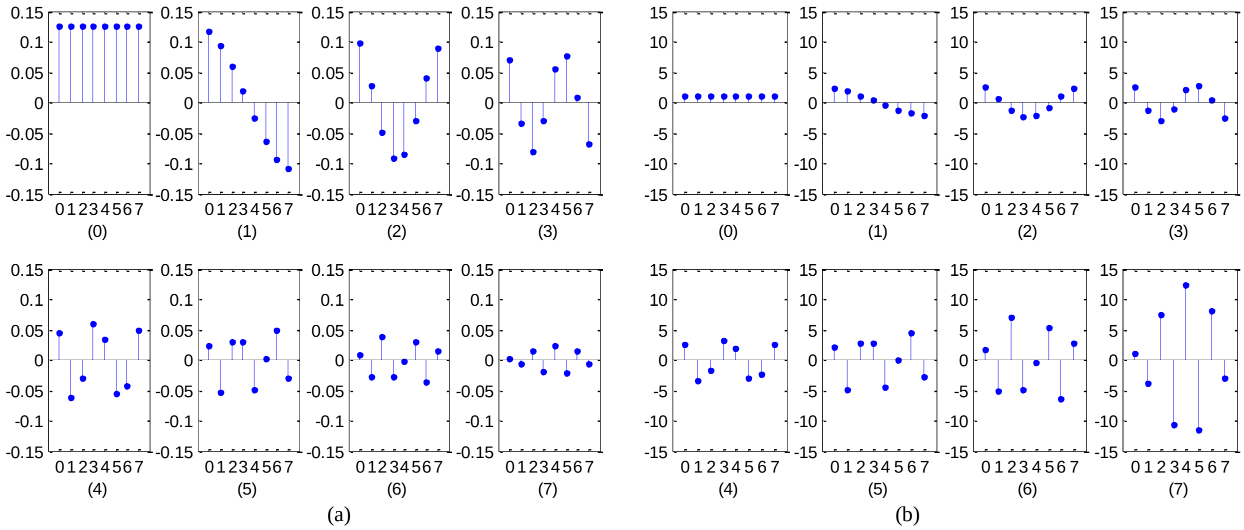


Fig. 2. The basis vectors of APIDSBT (N=8): (a) $\boldsymbol{V}$ and (b) $\boldsymbol{V}^{-1}$.

$$\boldsymbol{E} = \begin{bmatrix} 1.00 & 2.43 & 3.24 & 4.53 & 6.80 & 11.33 & 22.67 & 68.00 \\ 2.43 & 5.90 & 7.86 & 11.01 & 16.51 & 27.52 & 55.05 & 165.14 \\ 3.24 & 7.86 & 10.49 & 14.68 & 22.02 & 36.70 & 73.40 & 220.19 \\ 4.53 & 11.01 & 14.68 & 20.55 & 30.83 & 51.38 & 102.76 & 308.27 \\ 6.80 & 16.51 & 22.02 & 30.83 & 46.24 & 77.07 & 154.13 & 462.40 \\ 11.33 & 27.52 & 36.70 & 51.38 & 77.07 & 128.44 & 256.89 & 770.67 \\ 22.67 & 55.05 & 73.40 & 102.76 & 154.13 & 256.89 & 513.78 & 1541.33 \\ 68.00 & 165.14 & 220.19 & 308.27 & 462.40 & 770.67 & 1541.33 & 4624.00 \end{bmatrix}. \tag{11}$$

Fig. 3 shows the basis images of APIDSBT when N=8. Similar to DCT and DST, the lowest frequency component is located in the upper left corner whereas the highest frequency component is located in the lower right corner.

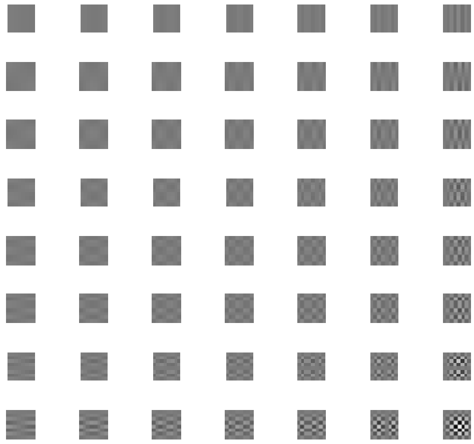
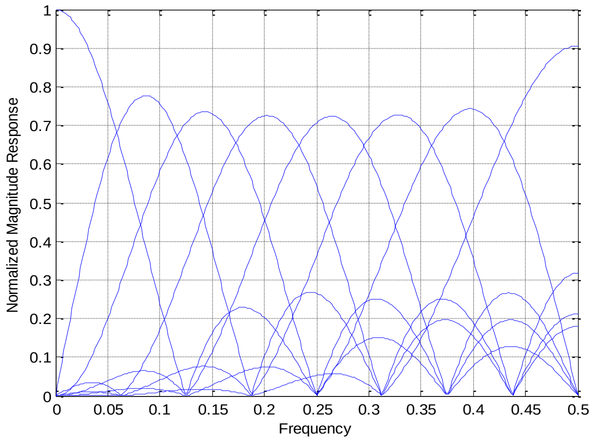


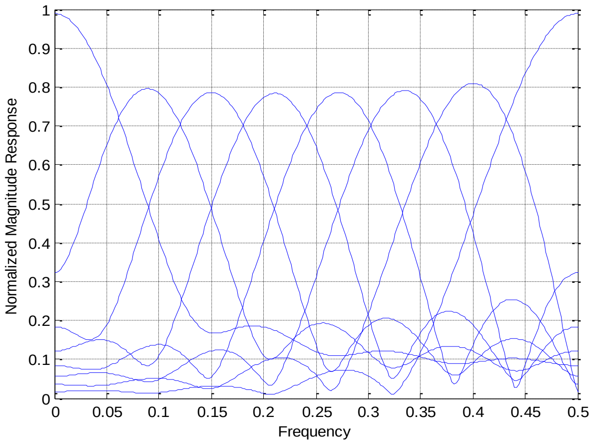
Fig. 3. The basis images of APIDSBT (N=8).

Considering the Frobenius norm of an image matrix as the energy of the image, the normalized energy of APIDSBT basis images with size of 8×8 is given in Eq. (11). One element in matrix $\boldsymbol{E}$ is corresponding to one basis image.

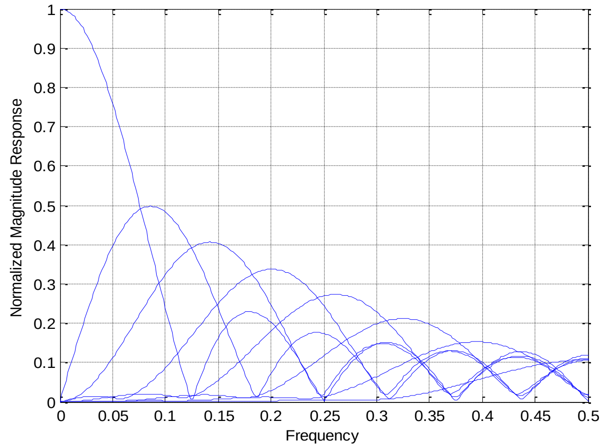
According to Fig. 3 and Eq. (11), we know that the energy of basis images increases with the increase of frequency along the down/right diagonal direction. Correspondingly, the transform coefficients in each transform block have a decreasing tendency along the same direction due to the fact that an image block can be considered the weighted sum of transform coefficients and their corresponding basis images essentially.



(a)



(b)



(c)

Fig. 4. The normalized magnitude responses of each filter (N=8): (a) DCT [10], (b) DST, and (c) APIDSBT.

In addition, we compare the normalized frequency responses of the filters in DCT, DST, and APIDSBT, shown in Fig. 4. From the view of frequency analysis, the energy of image is more concentrative by using APIDSBT than DCT or DST. APIDSBT can transfer more image energy to the low frequency part and gather them together.

C. The Application of APIDSBT in JPEG-Like Image Coding

It is indicated that the transform coefficients of APIDSBT have the high-frequency attenuation characteristics, that is to say, the transform coefficients have been weighted differently during the transform process. Therefore, the uniform quantization interval can be applied. The basic steps are substantially the same as those of the DCT-JPEG image compression algorithm, and the differences are only in the transform (DCT or APIDSBT) and the quantization (quantization table or uniform quantization step) processes, as shown in Fig. 5.

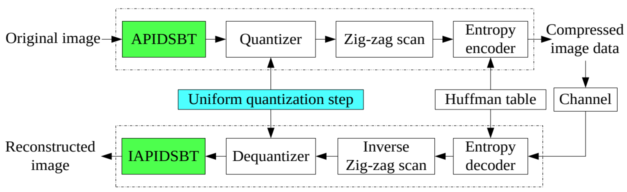


Fig. 5. The proposed APIDSBT-JPEG image codec.

In the encoding process, the image is firstly divided into 8×8 pixel blocks, according to the raster scan order, and then the APBT is applied to each pixel block. The uniform quantization interval is adopted to the transform coefficients, and the following steps are Zig-zag scan and entropy encoding. Wherein, the entropy encoder adopts the Huffman table suggested by JPEG standard. Contrary to the encoding process, the decoding process includes entropy decoder, inverse Zig-zag scan, dequantization, and Inverse APIDSBT (IAPIDSBT), and then the reconstructed image is obtained.

IV. Experimental Results and Comparative Analysis

To test the performance of the proposed APIDSBT transform and compare it with other transforms, we apply them to image coding scheme on typical test images Lena and Barbara. Both of them are 8 bit/pixel (bpp), monochrome images with size of 512×512. The original format is BMP. The PSNR is chosen to measure the distortion between the reconstructed image and the original one. Throughout this paper, all experiments are conducted with MATLAB R2012a.

Table I and Table II show the experimental results of DST-JPEG, DCT-JPEG, APDCBT-JPEG, and APIDSBT-JPEG in terms of PSNR at different bit rates, applied to image Lena and image Barbara, respectively.

TABLE I: PSNR COMPARISON BETWEEN APIDSBT-JPEG AND OTHER JPEG-LIKE ALGORITHMS ON IMAGE LENA

Bit Rate / bpp	**PSNR / dB**			
	DST-JPEG	**DCT-JPEG [10]**	**APDCBT-JPEG [10]**	**APIDSBT-JPEG**
0.15	20.00	25.82	26.76	27.21
0.20	22.16	28.91	29.16	29.39
0.25	23.48	30.69	30.67	30.89
0.30	24.46	31.92	31.72	31.98
0.40	26.41	33.62	33.30	33.66
0.50	27.73	34.74	34.40	34.84
0.60	28.84	35.61	35.27	35.75
0.75	30.28	36.62	36.33	36.85
1.00	32.21	37.93	37.63	38.19
1.25	33.72	39.00	38.65	39.22

TABLE II: PSNR COMPARISON BETWEEN APIDSBT-JPEG AND OTHER JPEG-LIKE ALGORITHMS ON IMAGE BARBARA

Bit Rate / bpp	**PSNR / dB**			
	DST-JPEG	**DCT-JPEG [10]**	**APDCBT-JPEG [10]**	**APIDSBT-JPEG**
0.15	18.05	22.04	22.56	22.79
0.20	19.61	23.47	23.66	23.84
0.25	20.57	24.36	24.39	24.64
0.30	21.24	25.11	25.14	25.44
0.40	22.49	26.55	26.59	26.91
0.50	23.64	27.90	27.85	28.24
0.60	24.61	29.20	28.99	29.48
0.75	25.95	30.88	30.49	31.15
1.00	28.02	33.22	32.53	33.38
1.25	29.84	35.10	34.19	35.17

From Table I and Table II, we conclude that at the same bit rates, the performance of APIDSBT-JPEG algorithm is superior to other JPEG algorithms in terms of PSNR.

To compare the compression performance subjectively, Fig. 6 and Fig. 7 show the reconstructed images Lena and Barbara of size 512×512 obtained by using DST-JPEG, DCT-JPEG, APDCBT-JPEG, and APIDSBT-JPEG at the same bit rate 0.20 bpp.

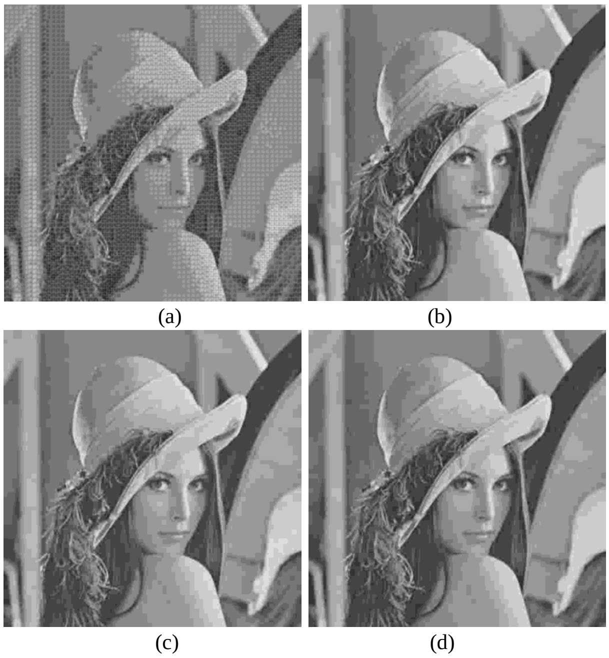


Fig. 6. Lena images obtained at 0.20 bpp: (a) DST-JPEG, with PSNR=22.16dB, (b) DCT-JPEG, with PSNR=28.91 dB, (c) APDCBT-JPEG, with PSNR=29.16dB, and (d) APIDSBT-JPEG, with PSNR=29.39dB.

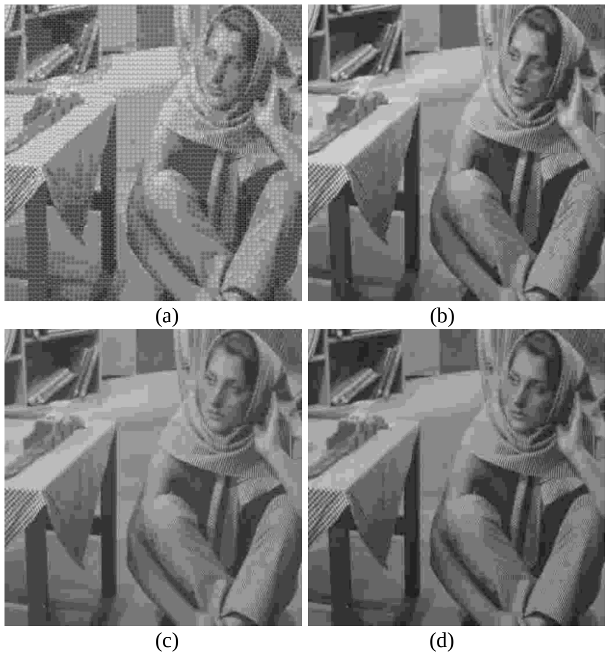


Fig. 7. Barbara images obtained at 0.20 bpp: (a) DST-JPEG, with PSNR=19.61dB, (b) DCT-JPEG, with PSNR=23.47 dB, (c) APDCBT-JPEG, with PSNR=23.66dB, and (d) APIDSBT-JPEG, with PSNR=23.84dB.

From the experimental results, we can see that compared with conventional JPEG, the proposed transform used in JPEG-based image coding algorithm improves the performance significantly at low bit rates, both in terms of PSNR and visual quality. Meanwhile, blocking artifacts of the reconstructed images have been reduced obviously.

Finally, we would like to point out that the proposed transform and the JPEG-like image coding scheme can also be applied to other images, and similar results and conclusions would be obtained.

V. Conclusions

This paper proposes a new transform called all phase inverse discrete sine biorthogonal transform based on APBT and IDST. We successfully apply it to image coding by replacing DCT, which is commonly used in JPEG image compression. By inheriting good properties from APBT-JPEG, taking the simple uniform quantization for transform coefficients can save many multiplication operations when adjusting the bit rates. The objective and subjective experimental results presented clearly exhibit an improvement over existing approaches in terms of PSNR and visual quality while keeping low computational complexity.

In the future, we will continue to explore other applications of APIDSBT, such as color image coding, video coding, and image watermarking. Furthermore, the parallel algorithm using GPU will be focused to accelerate the speed of image processing and analysis. These issues are left for further research.

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