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A Hybrid SPIHT-EBC Image Coder

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***Abstract*—Embedded zero-tree coding in wavelet domain has drawn a lot of attention to the image compression applications. Among noteworthy zero-tree algorithms is the SPIHT algorithm. For images with textures, high frequency wavelet coefficients are likely to become significant after few scan passes of SPIHT, and therefore the coding results are often insufficient. It is desirable that the low frequency and high frequency components of an image are coded using different strategies. In this paper, we propose a hybrid algorithm using SPIHT and EBC (embedded block coding) to code low frequency and high frequency wavelet coefficients, respectively; the intermediate coding results of low frequency coefficients are used to facilitate the coding operation of high frequency coefficients. Experimental results show that the coding performance can be significantly improved by the hybrid SPIHT-EBC algorithm.**

***Index Terms*—wavelet transform, SPIHT, embedded block coding, hybrid coding.**

I. INTRODUCTION

Wavelet transform provides numerous desirable properties, such as efficient multi-resolution representation, scalability, and embedded coding with progressive transmission, which are beneficial to the image compression applications [1]. Wavelet based multi-resolution representation matches the Human Visual System, specifically the higher detail information of an image is represented by the shorter basis function with higher spatial resolution and the lower detail information is represented by the larger basis function with higher spectral resolution [2]. The recently standardized image compression scheme known as JPEG 2000 uses discrete wavelet transform as the underlying transform algorithm [3].

After wavelet transform, the original image is decomposed into subbands with orientation selectivity. If a wavelet coefficient (in a subband) is insignificant, all the spatially related wavelet coefficients (in the higher frequency subbands of the same orientation) are likely to be insignificant and therefore they can be efficiently coded. Shapiro introduced the aforesaid self-similarity of wavelet coefficients in his embedded zero-tree wavelet (EZW) algorithm [4]. The improved EZW known as the set partitioning in hierarchical trees (SPIHT) algorithm has become a benchmark in image compression [5]. In SPIHT, the wavelet coefficients of an image are efficiently examined against a sequence of successively smaller threshold values to locate significant ones. Mukherjee and Mitra extended the SPIHT algorithm by performing set partitioning and significance testing on vectors of wavelet coefficients [6].

Besides such efficient algorithms as EZW and SPIHT making use of the pyramid structure of wavelet transform, there are some others taking advantage of the essential feature of wavelet coefficients known as energy clustering within each subband [7]-[10]. Said and Pearlman utilized quadtree partitioning to divide regions of high-energy coefficients into small blocks and regions of low-energy coefficients into large blocks in their amplitude and group partitioning (AGP) algorithm [8]. The set partitioning embedded block (SPECK) algorithm employs both quadtree partitioning and octave-band partitioning to repeatedly divide the wavelet transform coefficients of an image until significant coefficients are identified [9]. The embedded block coding with optimized truncation (EBCOT) algorithm first divides each wavelet subband into small blocks called code blocks, and then encodes each code block using an adaptive arithmetic coder known as the MQ coder [10]. The derived probability models of the MQ coder are based on the neighboring coefficients (of a transform coefficient).

For images with textures, many high frequency wavelet coefficients are likely to become significant after few scan passes of SPIHT and therefore the coding results are often insufficient. Thus, high frequency wavelet coefficients need to be encoded in a more suitable manner. Wavelet packet transform that provides a much larger family of basis functions than wavelet transform has been used to decompose high frequency wavelet coefficients into wavelet packet coefficients to improve the coding performance [11]-[12]. In this paper, we propose a hybrid algorithm using SPIHT and EBC to code the low frequency and high frequency wavelet coefficients of an image, respectively; the intermediate coding results of low frequency wavelet coefficients are used to guide the coding operation of high frequency wavelet coefficients. One of the advantages of hybrid SPIHT-EBC coding is that the well defined hierarchical structure across wavelet subbands and energy clustering within each wavelet subband can be taken into account to facilitate the image compression task.

The remainder of this paper proceeds as follows. In Section II, wavelet transform, the SPIHT algorithm, and embedded block coding in wavelet domain are briefly reviewed. Section III describes the proposed hybrid SPIHT-EBC algorithm. Experimental results are presented in

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Section IV. Conclusion is given in Section V.

II. REVIEW OF SPIHT AND EMBEDDED BLOCK CODING (EBC)

Wavelet transform provides an efficient multi-resolution analysis with numerous desirable properties, such as joint space-spatial frequency localization, high correlation across wavelet subbands and energy clustering within each subband. Figure 1(a) shows an example of 3-level 2-D wavelet transform, where HL_ℓ , LH_ℓ and HH_ℓ denote subbands of wavelet coefficients $D_\ell^1(m,n)$, $D_\ell^2(m,n)$ and $D_\ell^3(m,n)$ representing the detail information at resolution ℓ in the horizontal, vertical and diagonal orientations, respectively; LL_3 denotes the lowest frequency subband (composed of scaling coefficients $S_3(m,n)$), which represents the approximation at the coarsest resolution 3. The original image can be taken as $S_0(m,n)$ at the finest resolution 0. After 1-level wavelet transform, $S_\ell(m,n)$ is decomposed into $S_{\ell+1}(m,n)$, $D_{\ell+1}^1(m,n)$, $D_{\ell+1}^2(m,n)$ and $D_{\ell+1}^3(m,n)$. Moreover, $S_\ell(m,n)$ can be exactly reconstructed from $S_{\ell+1}(m,n)$, $D_{\ell+1}^1(m,n)$, $D_{\ell+1}^2(m,n)$ and $D_{\ell+1}^3(m,n)$ by inverse wavelet transform.

A. *Review of SPIHT*

After wavelet transform, an image is decomposed into subbands with orientation selectivity. The related wavelet coefficients taken from all the subbands of the same orientation can be grouped to form hierarchical trees, where the tree hierarchy is based on the resolution level. The root node of a tree is a coefficient at the coarsest resolution, and the leaf nodes are coefficients at the finest resolution. Every non-leaf node can be a parent node, which has four children nodes at the next finer resolution. For example, Fig. 1(b) shows a tree of wavelet coefficients in the diagonal orientation. For images with most of energies concentrated in the low frequency subbands, if a parent node is insignificant with respect to a given threshold, all the descendant nodes (at the finer resolution levels) are likely to be insignificant with respect to the same threshold, and therefore this tree of insignificant nodes called zero-tree can be efficiently coded. The above-mentioned property known as the self-similarity of wavelet transform motivates zero-tree coding in wavelet domain [4]-[5].

In the SPIHT algorithm, three symbols, namely zero-tree (ZT), insignificant pixel (IP) and significant pixel (SP) are used to code the wavelet coefficients of an image, which are stored in the list of insignificant sets (LIS), list of insignificant pixels (LIP) and list of significant pixels (LSP), respectively. The SPIHT algorithm is as follows.

1) Initialization: Set the initial threshold $T = 2^b$, where $b = \lfloor \log_2 (\max |c_{m,n}|) \rfloor$, and $c_{m,n}$ is the transform coefficient at position (m,n) .

2) Sorting pass: Identify significant coefficients with $T \le |c_{m,n}| < 2T$ and output their respective sign bits.

3) Refinement pass: For coefficients with $|c_{m,n}| \ge 2T$, output the b^{th} bit.

4) Decrease b by one, divide the threshold value by 2, and go to step 2.

The scan pass, i.e. sorting pass followed by refinement pass is repeatedly performed until the desired bit rate is reached. In sorting pass, if an insignificant coefficient stored in LIP becomes significant, it is removed to LSP and the sign bit is encoded; otherwise, it remains in LIP. For a tree of insignificant coefficients with the root stored in LIS, if none of the descendent coefficients becomes significant, the root remains in LIS; otherwise, it becomes a broken tree and a further decomposition takes place to locate the significant coefficients. In refinement pass, every significant coefficient that has been identified in previous sorting passes and stored in LSP is refined by updating the magnitude information.

B. *Review of EBC*

The main idea behind embedded block coding (EBC) is to make use of the energy clustering property of wavelet transform. The embedded block coding with optimized truncation (EBCOT) algorithm, which has been adopted by JPEG 2000, is a two-tier algorithm. Tier-1 performs bit-plane coding (BPC) followed by arithmetic coding. Tier-2 performs rate distortion optimization [10]. The coding passes of EBCOT, namely significance propagation pass, magnitude refinement pass, and cleanup pass are performed in BPC with four primitive coding operations: significance coding operation, sign coding operation, magnitude refinement coding operation, and cleanup coding operation. For each insignificant coefficient, if none of the 8-neighbor coefficients has become significant, it is coded by cleanup coding operation in cleanup pass; otherwise, it is coded by significance coding operation in significance propagation pass. If an insignificant coefficient becomes significant, the sign bit is then coded by sign coding operation. For each significant coefficient that has been identified in previous coding passes, the magnitude information is updated by magnitude refinement coding operation in magnitude refinement pass. The output bit-streams of BPC can be further compressed by arithmetic coding. The context-based adaptive arithmetic coder called the MQ coder has been adopted by JPEG 2000. Based on the present status of the 8-neighbor coefficients of a transform coefficient, the MQ coder defines 18 context labels, specifically 10 context labels are defined for significance coding operation and cleanup coding operation, 5 context labels for sign coding operation, and 3 context labels for magnitude refinement coding operation. EBCOT can be implemented in parallel, and moreover the throughput of EBCOT is independent of the image size due to the block coding strategy.

III. HYBRID CODING ALGORITHM USING SPIHT AND EBC

High quality image compression can be achieved by coding the wavelet coefficients of an image adaptively. For images with high-detail textures, lots of high frequency wavelet coefficients are found significant and therefore the simple SPIHT algorithm may not be sufficient. Figure 5(c), for example, shows a gray scale Fingerprint image composed mainly of high frequency ring textures. The constructed wavelet trees of Fingerprint are examined against a sequence of successively smaller thresholds. For each zero-tree, if any of the constituent nodes become significant, this zero-tree is called broken tree and needs to be further divided into sub-trees. We count the number of broken trees caused by significant non-offspring descendant nodes in comparison with various threshold values. As shown in Table I, there are a large percentage of broken trees caused by significant non-offspring descendant nodes in the 3rd scan pass of SPIHT (35.4 %) for Fingerprint image. In contrast to Fingerprint image, Lena image (shown in Fig. 5(a)) is representative of typical images with most of energies concentrated in the low frequency subbands, and therefore the percentages of broken trees caused by significant non-offspring descendant nodes are rather small (3.4 % in the 3rd scan pass of SPIHT). Thus, there is no reason to doubt that the low frequency and high frequency wavelet coefficients of images with textures need to be coded differently in order to improve the overall coding performance.

Table I: Percentage of broken trees caused by significant non-offspring descendant nodes in comparison with threshold T_k $(k = 1, 2, \cdots; T_{k+1} = 0.5T_k)$

	Lena	Fingerprint
T_1	0 %	0 %
T_2	0 %	0 %
T_3	3.4 %	35.4 %
T_4	7.2 %	16.4 %

Take the Airplane image shown in Fig. 5(b) as another example. We analyze the coding results of low frequency wavelet coefficients with or without the influence of the highest frequency wavelet coefficients. As shown in Fig. 2, where the horizontal and vertical axes are the bit rates and mean squared error (MSE) values, respectively, the dotted curve obtained by SPIHT without the influence of the highest frequency coefficients is preferable to the solid curve (with the influence of the highest frequency coefficients). Thus, a hybrid strategy is proposed to code the low frequency coefficients (without the influence of the highest frequency coefficients) and the highest frequency coefficients independently.

A. *Hybrid Coding of Wavelet Coefficients*

In many cases, an image is composed of homogeneous regions, textures and edges, which are the low, middle-high and high frequency components, respectively. Most of the significant wavelet coefficients representing homogeneous regions are in the low frequency subbands, but by contrast the significant wavelet coefficients representing the noticeable textures and edges are often in the higher frequency subbands. Though de-correlation of wavelet coefficients is a feature of wavelet transform, there may still be residual correlation between neighboring wavelet coefficients. In addition, the significant high frequency wavelet coefficients of an image are likely to be clustered. Thus, a context-based embedded block coding (EBC) strategy is suitable for coding the highest frequency wavelet coefficients. Figure 3 depicts the proposed algorithm using SPIHT and EBC to code the low frequency and the highest frequency wavelet coefficients, respectively. The detail of the hybrid SPIHT-EBC algorithm is as follows.

B. *Hybrid SPIHT-EBC Algorithm*

1) Initialization: Decompose the original image into wavelet subbands. Quantize the transform coefficients with a given step-size to form the bit-plane representation so that the image is coded bit-plane by bit-plane, from most to least significant.

2) Sorting pass for the upper tree levels: As tree nodes at the upper levels are wavelet coefficients in the lower frequency subbands, which represent the homogeneous regions of an image, the sorting pass of SPIHT is therefore adopted to code these tree nodes.

3) Significance propagation pass for the leaf nodes: By comparison with the sorting pass of SPIHT, it is noted that the significance propagation pass of EBCOT is preferable for locating the significant leaf nodes, which are the highest frequency wavelet coefficients representing the high-detail textures of an image. Thus, for a leaf node that is insignificant at the moment, if its parent node is significant and at least one of the 8 neighboring nodes is also significant, this leaf node is coded in this pass; otherwise, it will be coded in the later pass called cleanup pass.

4) Magnitude refinement pass: The significant nodes that have been found in previous coding passes are refined with one bit per node.

5) Cleanup pass for the leaf nodes: For the insignificant leaf nodes that have not been coded in the previous significance propagation pass, examine and code these nodes using the context-based cleanup coding operation of EBCOT. In addition, if the parent node (at the next upper level) and the 12 neighboring leaf nodes (shown in Fig. 4) are all insignificant, then the 4 leaf nodes are coded by a single run-length coding with or without the uniform coding operation of EBCOT.

6) Go to step 2, and code the next less significant bit-plane.

The proposed hybrid coding algorithm is performed in the framework of SPIHT so that the advantage of the pyramid structure of wavelet transform can be taken into account. As energies of the low frequency components of an image are likely to decrease from low to high frequency subbands, wavelet nodes at the upper tree levels can be efficiently coded by using SPIHT. On the other hand, as the significant wavelet coefficients in the highest frequency subbands are likely to be clustered, the leaf nodes are thus coded by using the significance propagation pass and cleanup pass of EBCOT instead of the sorting pass of SPIHT. The sequence of coding passes from step 2 to step 5 is repeatedly performed until a given bit rate (or the reconstructed image quality) is reached. In sorting pass, if all the descendant nodes of a zero-tree are still insignificant, excluding the leaf nodes that are to be coded in either significance propagation pass or cleanup pass, they remain a group of insignificant nodes and therefore can be efficiently coded by using a single symbol, ZT. Note that the output of coding step 2 has been used as an estimate of significance to facilitate the following coding step such that significant nodes can be coded as early as possible. For each insignificant node, if it becomes significant, its sign bit is immediately coded. The resulting code stream of the proposed SPIHT-EBC algorithm is still embedded and progressive, and moreover, it can be implemented in quad-tree parallel.

IV. EXPERIMENTAL RESULTS

The proposed hybrid SPIHT-EBC algorithm has been evaluated on several grayscale images. The coding results of images namely Lena, Airplane and Fingerprint (shown in Fig. 5) are presented in this paper. The linear phase bi-orthogonal wavelet with 9/7-coefficient filter set is used. The number of wavelet decomposition levels is 6. Sorting pass in coding step 2 is performed on the tree nodes from the top level to level 5. Significance propagation pass in coding step 3 and cleanup pass in coding step 5 are performed on the leaf nodes (at the bottom level). The compression rate is measured in bits per pixel (bpp). The distortion defined by peak signal to noise ratio (PSNR) is measured in dB. The resulting bit rates and PSNR values are taken to form rate distortion curves for comparisons. The coding performance of the proposed SPIHT-EBC algorithm is compared to that of the SPIHT algorithm.

There is a large portion of homogeneous regions in Lena image and therefore many significant wavelet nodes are found at the upper tree levels. As shown in Fig. 6, the SPIHT-EBC algorithm without entropy coding is comparable with the SPIHT algorithm with entropy coding, and furthermore, SPIHT-EBC with entropy coding marginally outperforms SPIHT with entropy coding.

For images with textures such as Airplane, lots of the leaf nodes are likely to become significant after few coding passes of SPIHT. Thus, the hybrid SPIHT-EBC algorithm is preferable to the SPIHT algorithm; even SPIHT-EBC without entropy coding is marginally preferable to SPIHT with entropy coding, as shown in Fig. 7.

Compression of fingerprints images is one of the most important issues and demands the best solution. Figure 8 shows the compression results of Fingerprint image. It is noted that SPIHT-EBC without entropy coding is still marginally preferable to SPIHT with entropy coding, and a further improvement in the rate distortion curve can be obtained by using SPIHT-EBC with entropy coding.

V. CONCLUSION

Wavelet transform has been adopted by JPEG 2000 as the underlying method to decompose an image into subbands with orientation selectivity. Wavelet transform provides numerous desirable properties, such as multiresolution analysis, high correlation between wavelet subbands of the same orientation, and energy clustering within each subband; these properties are suitable for the image compression applications. The development of the well-known SPIHT algorithm is based on the cross-subband similarity of wavelet transform. However, for a texture-rich image, the highest frequency wavelet coefficients are likely to become significant after few coding passes of SPIHT, and therefore the coding performance of SPIHT might not be sufficient. The highest frequency wavelet coefficients, which often represent the high-detail textures of an image, can be efficiently coded by taking advantage of the energy clustering of wavelet transform. As a result, SPIHT can be combined with embedded block coding (EBC) to form a hybrid image coder. In the proposed hybrid SPIHT-EBC algorithm, the low frequency wavelet coefficients of an image are coded by using SPIHT, the highest frequency wavelet coefficients are coded by using the tier-1 part of the famous EBCOT algorithm, and the intermediate coding results of low frequency wavelet coefficients are used to facilitate the coding task of the highest frequency wavelet coefficients so that the significant ones can be coded as early as possible. Experimental results show that the hybrid SPIHT-EBC coder outperforms SPIHT.

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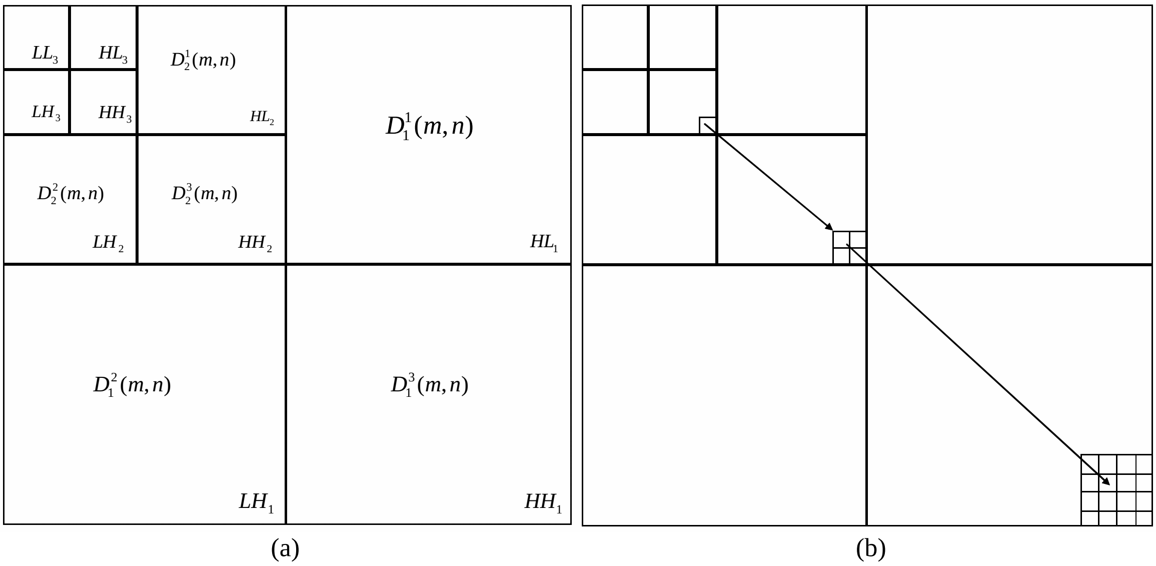


Fig. 1: 3-level wavelet transform (a): Subbands delimited by thick lines; (b): A hierarchical tree in the diagonal orientation.

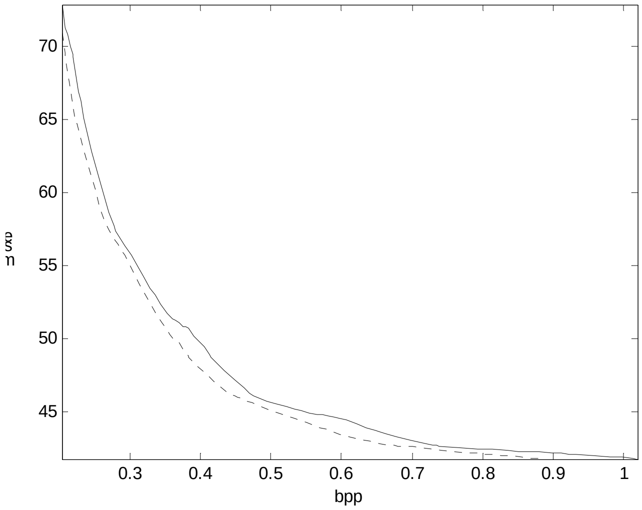


Fig. 2 Rate-distortion curves of the low frequency wavelet coefficients of Airplane image (shown in Fig. 5(b)) obtained by SPIHT with the influence of the highest frequency wavelet coefficients (solid line) and by SPIHT without the influence of the highest frequency wavelet coefficients (dotted line); Horizontal axis: bit rates; Vertical axis: mean squared error (MSE) values.

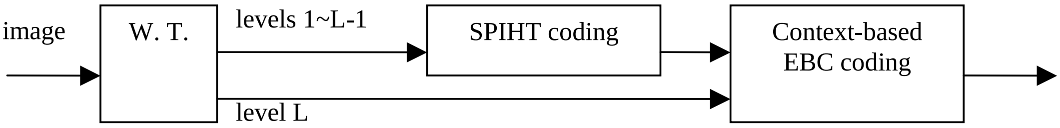


Fig. 3 Block diagram of the proposed SPIHT-EBC algorithm.

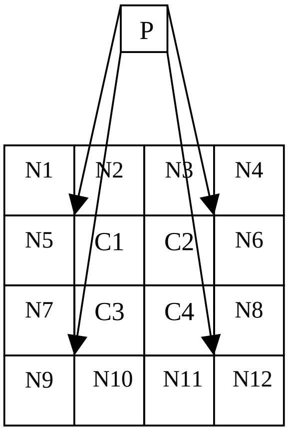


Fig. 4 The 12 neighboring nodes (N1-N12) of the 4 children nodes (C1-C4) of a parent node P.

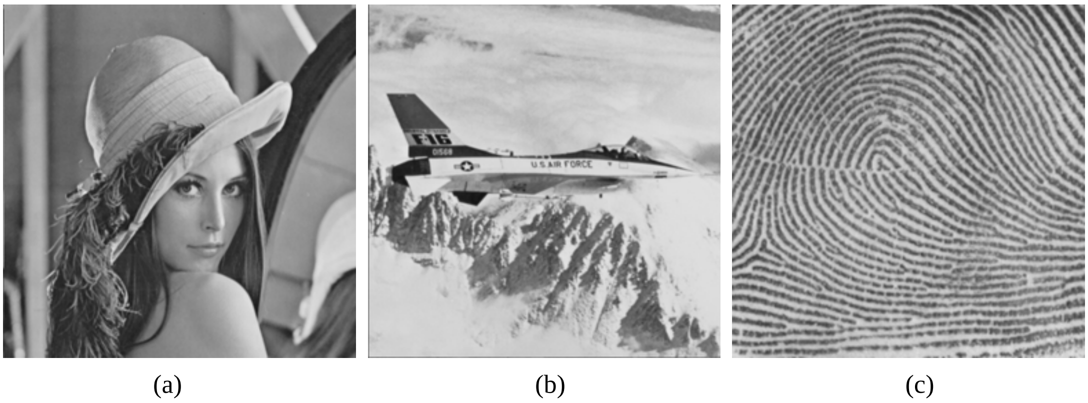
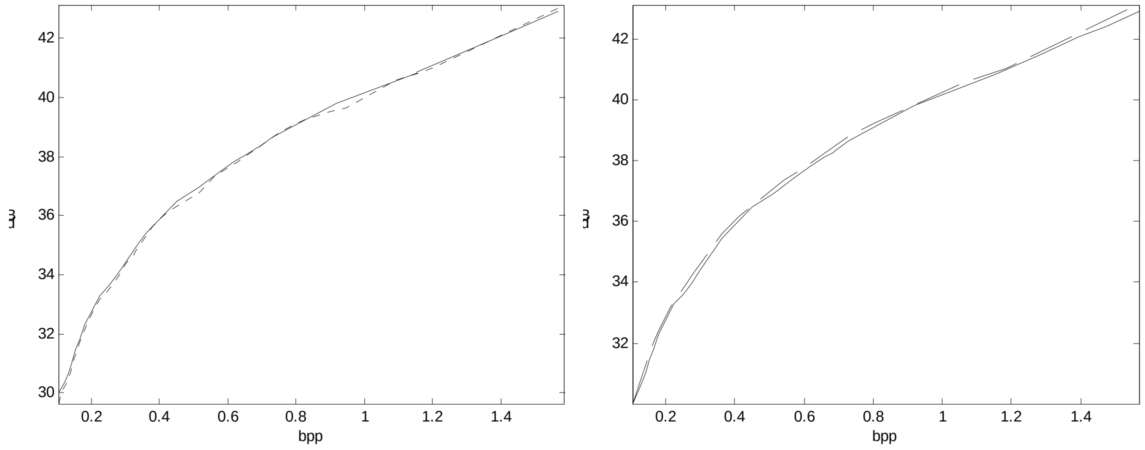
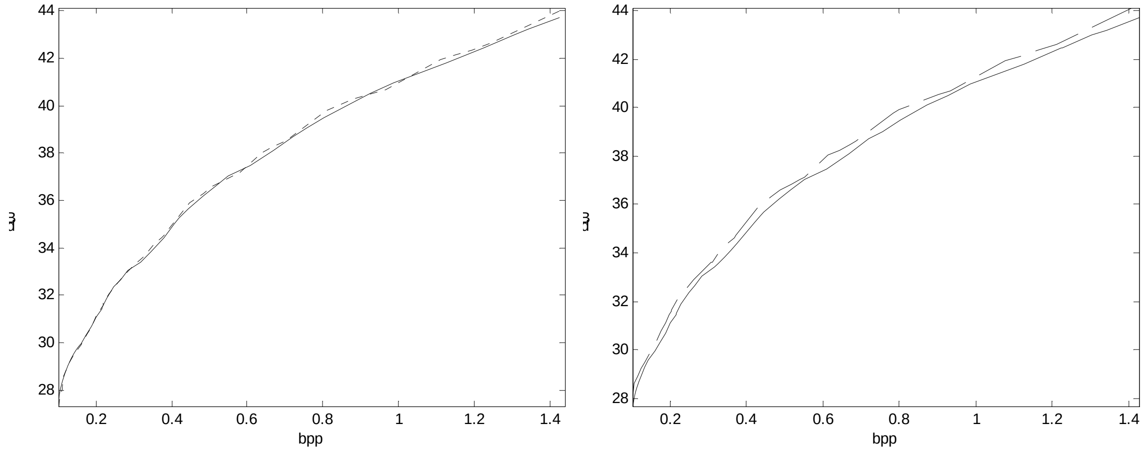

(a) (b) (c)

Fig. 5 Test images (a) Lena; (b) Airplane; (c) Fingerprint.



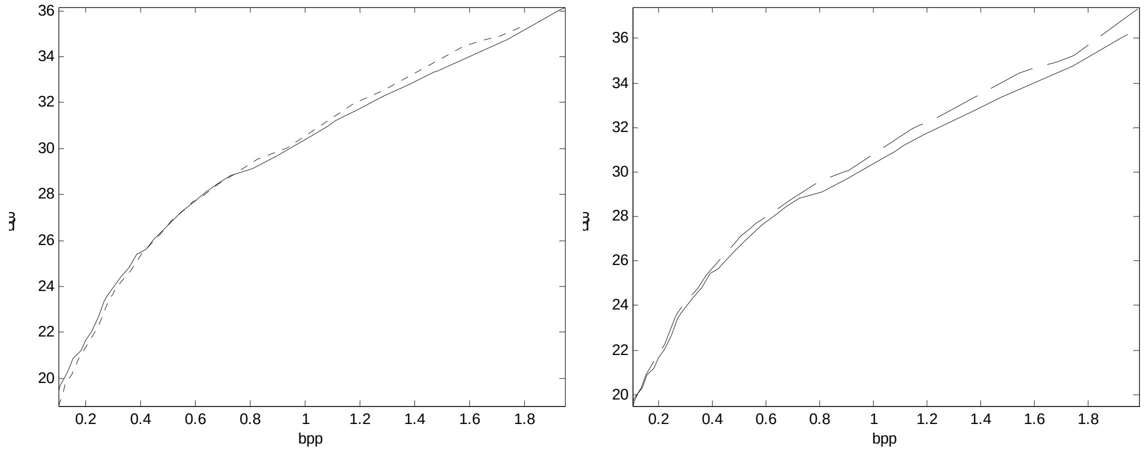
(a) (b)

Fig. 6 Rate-distortion curves of Lena image (a): Solid line: by SPIHT with entropy coding; Dotted line: by SPIHT-EBC without entropy coding; (b): Solid line: by SPIHT with entropy coding; Dashed line: by SPIHT-EBC with entropy coding.



(a) (b)

Fig. 7 Rate-distortion curves of Airplane image (a): Solid line: by SPIHT with entropy coding; Dotted line: by SPIHT-EBC without entropy coding; (b): Solid line: by SPIHT with entropy coding; Dashed line: by SPIHT-EBC with entropy coding.



(a) (b)

Fig. 8 Rate-distortion curves of Fingerprint image (a): Solid line: by SPIHT with entropy coding; Dotted line: by SPIHT-EBC without entropy coding; (b): Solid line: by SPIHT with entropy coding; Dashed line: by SPIHT-EBC with entropy coding.