SIGNIFICANCE-LINKED CONNECTED COMPONENT ANALYSIS FOR HIGH PERFORMANCE LOW BIT RATE WAVELET CODING

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Abstract - Recent success in wavelet image coding is mainly attributed to the recognition of importance of data organization and representation. There have been several very competitive wavelet coders developed, namely, embedded zerotree wavelets (EZW), morphological representation of wavelet data (MRWD), and set partitioning in hierarchical trees (SPIHT). In this paper, we develop a novel wavelet image coder called significance-linked connected component analysis (SLCCA) of wavelet coefficients that extends MRWD by exploiting both within-subband clustering of significant coefficients and cross-subband dependency in significant fields. Computer experiments on both natural and texture images show convincingly that the proposed SLCCA outperforms EZW, MRWD, and SPIHT as well. For example, for the "Barbara" image, at 0.50 bpp SLCCA outperforms EZW and SPIHT by 1.71 dB and 0.85 dB in PSNR, respectively. It is also observed that SLCCA works extremely well for images with a large portion of texture. This outstanding performance is achieved without using any optimal bit allocation procedure. Thus both the encoding and decoding procedures are fast.

INTRODUCTION

Since the 1980's, subband coding has been popularly used for image compression. Wavelet theory not only fundamentally identifies subband coding as wavelet's discrete cousins, but also provides a productive approach to designing subband filters. The latter is evidenced by the discovery of symmetric biorthogonal wavelet bases with compact support which are instantly converted into more desirable linear phase filters while maintaining a necessary perfect reconstruction. Thus subband and wavelet are often used interchangeably in the literature.

Conventional wavelet image coders [1, 2] mainly exploit the energy compaction property of subband decomposition by using optimal bit allocation strategies. Their drawback is apparent in that all zero-valued coefficients in wavelet fields must be represented and encoded, biting away a significant

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portion of the bit budget. Although these wavelet coders provides superior visual quality compared to block-based image coders such as JPEG, their objective performance increases only moderately. A fundamental issue with wavelet coding is: what are the statistical properties of wavelet-transformed images within or across subbands when images admit a model such as Markov random field? We will address this important issue in a separate paper.

In recent years, we have seen an impressive advance of wavelet image coding. The success is mainly attributed to innovative strategies for data organization and representation of wavelet-transformed images. There are three such wavelet image coders published, namely, Shapiro's embedded zerotree wavelet (EZW) [3], Servetto *et al.*'s morphological representation of wavelet data (MRWD) [4], and Said and Pearlman's set partitioning in hierarchical trees (SPIHT) [5]. They are all based on empirical observations of the statistical properties of wavelet-transformed images one way or the other. As a result, the PSNR of reconstructed images is consistently raised by 1–3 dB over block-based transform coders.

In this paper, we propose a new wavelet image coder called significance-linked connected component analysis (SLCCA) which exploits both within subband clustering of significant coefficients and cross-subband dependency in the significant field. SLCCA strengthens MRWD by exploiting cross-subband dependency among clusters.

OVERVIEW OF DATA ORGANIZATION AND REPRESENTATION STRATEGIES

Two distinct types of approaches are proposed for an efficient organization and representation of wavelet coefficients in the literature. We follows the definitions in [3] when discussing the coefficient relations in a wavelet pyramid. While EZW and SPIHT use the regular tree structures to approximate insignificant fields across subbands, MRWD finds irregular clusters of significant coefficients within subbands. Among the top three wavelet image coders, SPIHT performs the best in general.

EZW efficiently identifies and approximates arbitrary shaped zero regions across subbands by the union of highly constrained tree-structured zero regions called *zerotree*. Meanwhile, it defines the significant fields everywhere outside these zero regions through progressively refining coefficients' magnitudes. Apparently, each *zerotree* can be effectively represented by its root symbol. On the other hand, there may still be many zero coefficients which cannot be included in the highly structured zerotrees. These isolated zeros remain very expensive to represent.

SPIHT seeks to enhance EZW by partitioning the cross-subband tree structure into three parts, i.e., tree root, children of the root, and non-child descendents of the root. When a child coefficient is found significant, EZW has to represent and encode all four grandchild coefficients separately even if all non-child descendents are insignificant. By contrast, SPIHT treats the entire insignificant non-child descendents as a set and employs a single symbol to represent it. This fine set partitioning strategy leads to an impressive increase in PSNR.

Different from EZW and SPIHT, MRWD directly forms irregular shaped clusters of significant coefficients within subbands. Although the boundary zeros of each cluster still need to be represented, the expensive cost of representing and encoding isolated zeros in EZW is avoided. As a result, MRWD constantly outperforms EZW. Nevertheless, MRWD *does* need to specify a seed for each cluster and encode its positioning information as overhead. As a large number of clusters are involved, the overall overhead may take up a significant portion of the bit budget.

SIGNIFICANCE-LINKED CONNECTED COMPONENT ANALYSIS

Since a rather large portion of wavelet field appears insignificant and significant coefficients within subbands tend to be more clustered, organizing and representing each subband as irregular shaped clusters of significant coefficients provide an efficient way for encoding. Clusters are progressively constructed by using conditioned dilation operation, as sketched in [4]. Often it would be more efficient to only loosely form clusters since the conventional connected component analysis might result in too many connected components, affecting the coding efficiency. Thus we shall use symmetric structuring elements with a size larger than a 3×3 square, but still call segments generated by conditioned dilation *connected components* or *clusters*, even though they may not be geometrically connected. A connected component includes its boundary coefficients which are all zeros. The optimal choice of size and shape of structuring elements is determined by the cost spent on both encoding boundary zeros and positioning connected components.

The cross-subband similarity among *insignificant coefficients* in wavelet pyramid has been exploited in EZW and SPIHT that greatly improves the coding efficiency. On the other hand, it is found that the spatial similarity in wavelet pyramid is not satisfied strictly, i.e., an insignificant parent does not warrant all four children to be insignificant. The "isolated zero" symbol used in EZW indicates the failure of such a dependency. As was stated in [3] and [5], when the threshold decreases (for embedding) to a certain point, the tree structure or set-partitioned-tree structure are no longer efficient.

In the proposed algorithm, as opposed to EZW and SPIHT, we attempt to exploit the spatial similarity among *significant coefficients*. However, we do not seek for the very strong parent-child dependency for each and every significant coefficient. Instead, we try to predict the existence of clusters at finer scales. Theoretically, by assuming Markov random field as image model we are able to prove that statistically the magnitudes of wavelet coefficients decay from the *parent* to its *children*. It implies that in a significant cluster formed within a finer subband, there likely exists a *child* whose *parent* belongs to a significant cluster within a coarse subband. That is, a significant child can likely be traced back to its parent through *significance linkage*. It is crucial to note this *significance linkage* relies on a much looser spatial similarity.

Formally, two connected components or clusters are called *significance-linked* if the significant parent belongs to one component and at least one of its children is significant and lies in another component. If the positioning information of the significant parent in the first component is available, then the positioning information for the second component can be inferred when the parent is marked as having a significance-link. Apparently, marking costs much less than positioning and saving on positioning clusters is then achieved. Furthermore, as there are generally many significant coefficients in a component, the likelihood of finding significance-link between two components is high. The saving increases as the bit rate increases, ranging from 527 bytes (at 0.25 bpp) to 1183 bytes (at 0.5 bpp) in comparison to MRWD.

As in most image compression algorithms, the last step of SLCCA involves entropy coding for which adaptive arithmetic coding [6] is employed. In order to exploit the full strength of adaptive arithmetic coder, it is preferable to organize outcomes of a nonstationary Markov source into such a stream that the local probability distribution is in favor of one source symbol. Thus bit plane encoding is employed by SLCCA to match the probability model of the adaptive arithmetic coder with the local statistics.

PERFORMANCE EVALUATION

The performance of SLCCA is evaluated with two 512×512 gray scale images "Lena" and "Barbara" and compared to the best wavelet coders, EZW, MRWD, and SPIHT. In experiments, the original image is decomposed into a 6-scale subband pyramid using the 10/18 filters obtained from ftp.cs.dartmouth.edu. There is no optimal bit allocation carried out in SLCCA. Instead, all wavelet coefficients are quantized with the same uniform scalar quantizer.

Table shows the PSNR comparison among four wavelet coders on the "Lena" image at different bit rates. SLCCA consistently outperforms EZW, MRWD, and SPIHT as well. Compared to EZW, SLCCA gains 1.04 dB in PSNR on average. When compared to MRWD, SLCCA is superior by 0.23–1.04 dB. Compared to SPIHT, SLCCA gains 0.15 dB.

Table compares the performance of SLCCA, EZW, and SPIHT on the "Barbara" image. On average, SLCCA is superior to EZW by 1.67 dB, and to SPHIT by 0.62 dB.

The experiments seem to imply that SLCCA performs better than SPIHT for images which are rich in texture, such as "Barbara." Additional experiments on eight typical texture images confirms this observation. An explanation is as follows. When textured images are encoded, wavelet transform is unlikely to yield many large zero regions for lack of homogeneous regions. Thus, the advantage of using an insignificant tree as in EZW, or insignificant part-of-tree structure as in SPIHT is weakened. On the other hand, SLCCA uses significance-based clustering and significance-based between-cluster linkage, which are not affected by the existence of textures.

Algorithm/Rate [bpp]	0.125	0.25	0.30	0.40	0.50	1.00
EZW	30.23	33.17	-	-	36.28	39.55
MRWD	-	-	34.07	-	36.60	40.17
SPIHT	31.09	34.11	34.95	36.24	37.21	40.41
SLCCA	31.34	34.30	35.11	36.39	37.35	40.40

Table 1. Performance comparison (PSNR [dB]) on "Lena" image.

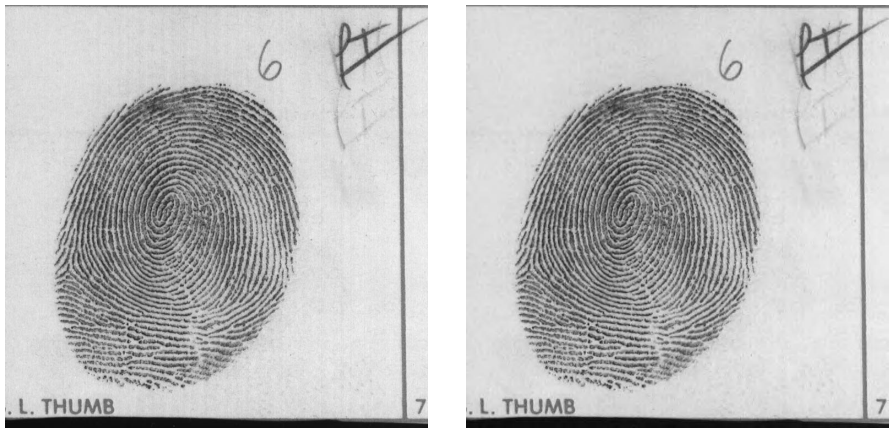
Algorithm/Rate [bpp]	0.125	0.25	0.30	0.40	0.50	1.00
EZW	24.03	26.77	-	-	30.53	35.14
SPIHT	24.86	27.58	28.56	30.10	31.39	36.41
SLCCA	25.40	28.39	29.35	30.89	32.24	37.12

Table 2. Performance comparison (PSNR [dB]) on "Barbara" image.

Finally, we apply SLCCA to fingerprint image compression, which represents a very important issue demanding the best solution. The FBI has developed a fingerprint image compression algorithm called wavelet scalar quantization (WSQ) [7]. At 0.444 bpp or 18:1 compression, SLCCA yields a PSNR of 35.81 dB as opposed to WSQ's 34.43 dB, corresponding to 1.38 dB improvement. The original and reconstructed images from SLCCA at 0.444 bpp are shown in Fig. . Note that there is little loss in visual quality.

CONCLUSIONS

A new image coding algorithm termed significance-link connected component analysis is proposed in this paper. SLCCA takes advantage of two properties of the wavelet decomposition: the within-subband clustering of significant coefficients and the cross-subband dependency in significant fields. The significance-link is employed to represent the positional information for clusters at finer scales, which greatly reduces the positional information overhead. The magnitudes of significant coefficients are coded in the bit plane order so that the local statistic in the bit stream matches the probability model in adaptive arithmetic coding to achieve further saving in bit rate. Extensive computer experiments justify that SLCCA surpasses the state-of-the-art image coding algorithms reported in the literature. As no optimization is involved, both the encoding and decoding procedures are remarkably fast.



(a) (b)

Figure 1. Coding result for "Fingerprint" image. (a) Original image. (b) Reconstructed image by SLCCA at 0.444 bpp, PSNR=35.57 dB.

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