Transactions Letters

Variable Complexity DCT Approximations Driven by an HVQ-Based Analyzer

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***Abstract*—Transform approximations are explored for speeding up the software compression of images and video. Approximations are used to replace the regular discrete cosine transform (DCT) whenever only a few DCT coefficients are actually encoded. We employ a novel hierarchical vector quantization (HVQ)-based image analyzer to drive a bank of coders, thus switching to the fastest coder depending on the image contents: smoother areas would produce less bits than detailed ones but faster. The HVQ analyzer is fast and simple enough to not offset the complexity gains brought by the DCT approximations. The approximations in this paper are applicable to high compression environments, where lower complexity is also required.**

***Index Terms*—Color fax, DCT, fast algorithms, JPEG, MPEG, transform coding.**

I. Introduction

In SEVERAL image transmission systems, the image data is input or generated *on-the-fly* and transmitted immediately. This is the case in live transmission of video and stills. In color fax, image parameters are only determined after handshaking. Hence, as is the case of live production of stills and video, compression has also to be performed in real time. Compression standards such as JPEG [1] or MPEG [2] rely on sequential transform, quantization, and entropy coding. Typically, all image data is transformed and quantization is applied to every transformed coefficient. These two steps typically drain a significant fraction of the compression computation and are independent of the image data or of the compression target. Hence, while the contents change along the image, the number of bits produced per image block also changes, but there is little change in compression time. As a result, the rate in bits per second that the compressor produces would change significantly from smooth regions to active ones. The problem is that in several transmission systems, such as modems for color fax, the transmission rate is fixed. A buffer can control and homogenize the speed for the modem, but, if the compressor is not fast enough, the buffer might underflow and the connection might time out.

In summary, we are concerned with systems in which software-based compression is performed *on-the-fly* and where it is desirable to reduce computational complexity either to homogenize the bit-rate production or to reduce costs. Our goal is to speed up the compression by replacing the real transformation with a low-cost approximation.

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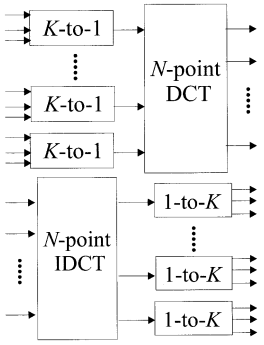


Fig. 1. Approximated transform to approach a reduced M-point DCT ($M = NK$).

II. Approximating Reduced Transforms

In this paper, we examine the case of the discrete cosine transform (DCT) and concentrate exclusively in the JPEG image coding standard, although results would also apply to MPEG. Let blocks have $M \times M$ pixels and assuming a separable two-dimensional (2-D) DCT, we can analyze a one-dimensional (1-D) M-point DCT. Imagine that some blocks have no high-frequency content or that quantization would remove the high-frequency coefficients in such a way that fewer than M coefficients are actually needed. In this paper's context, a *reduced transform* is the one wherein only N out of M coefficients are actually generated (see, for example, [3] and [4]). This can be accomplished by pruning an M-point transform, but if one needs to retain only N lower frequency coefficients where $M = KN$, there is a "short-cut" for approximating the generation of these coefficients as shown in Fig. 1. In this figure, the reduced $M : N$ DCT can be approximated by an N-point DCT, by first reducing the input vector by means of a K-to-1 reduction (e.g., pixel averaging). The expansion also, from the N low frequency coefficients to the M samples, can be approximated as in Fig. 1. The method is based on interpolation in the DCT domain and is further studied in [5]–[8]. Like in the forward case, the 1-to-K expansion can be the "nearest neighbor" or any other simple interpolation method.

In the JPEG case, typical values are $N = 1, 2, 4$, i.e., reductions are $K = 8, 4, 2$, respectively. For example, in the case $N = 1$, only the dc is computed. This is done so by averaging all the 64 samples in the input block. Only one sample is quantized and there is no need for entropy coding the ac terms. For decompression, the DC term is directly dequantized and replicated for all the 64 block pixels. When $N = 2$, there is an average of 4×4 subblocks and a very simple DCT (DCT-2 is the Haar transform [5]).

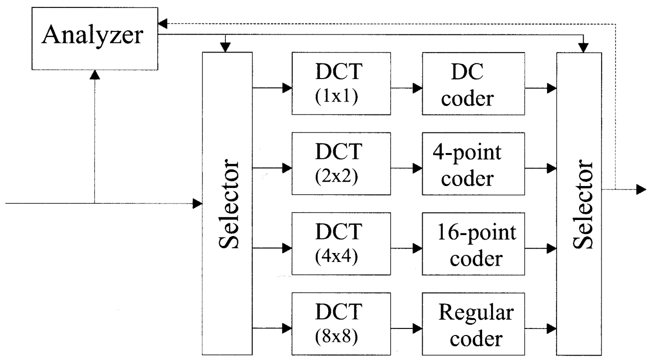


Fig. 2. Fast DCT coder based on multiple reduced DCT and multiple coders.

Apart from reduced-frequency DCT methods such as [3] and [4], there are also other efficient methods to simplify the DCT step [9]–[11]. This paper's new ingredients are the bank of reduced trasnsforms and a front-end analyzer that is fast and robust enough to drive the effective switch among the reduced transforms. In fact, our analyzer can be used to aid the methods in [3], [4], [10], and [11].

The use of the reduced transforms may result in signal losses which can be further emphasized through their approximations. It is advisable to only apply the reduced transforms whenever there is no need for the high-frequency information.

III. Transform Adaptation

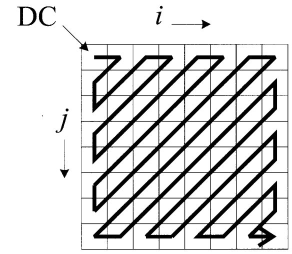
Straight application of the reduced transforms can cause image degradation. In the best scenario, the image block is analyzed and one coder is selected based on image contents, so that it would save computation without compromising the image quality. The analyzer complexity overhead has to be such as to not offset the gains obtained by switching transforms. The overall diagram is depicted in Fig. 2 for the JPEG case, where the encoding system is shown for $N = 1, 2, 4$, along with the normal encoder $(N = M = 8)$. Note that reduced transforms may also imply reduced compressors.

The key to select the coder is to determine if there are high-frequency contents in a block or not. Actually, one may want to use the smallest transform that would encompass all the relevant high frequency data in a block.

A. Decoder Adaptation

Decoder adaptation is trivial in the sense that one can observe the compressed data and compute the highest frequency nonzero DCT coefficient in a block. In JPEG, the DCT coefficients are quantized and the block is scanned into a vector following a "zigzag" pattern [1]. Let $\{v(n)\}$ $(0 \leq n < 64)$ be the vector containing the 64 quantized samples of a given block. Referring to Fig. 3, one can easily identify which are the vector entries corresponding to the lowest frequency 1×1, 2×2, and 4×4 coefficients, e.g., $\{v(0), v(1), v(2), v(4)\}$ compose the lowest frequency 2×2 subblock.

The general process is to verify whether there are no nonzero coefficients outside the boxes in Fig. 3. However, testing too many coefficients can be costly and can partially offset the gains provided by reduced transforms. Let N_m be the maximum index



0	1	5	6	14	15	27	28
2	4	7	13	16	26	29	42
3	8	12	17	25	30	41	43
9	11	18	24	31	40	44	53
10	19	23	32	39	45	52	54
20	22	33	38	46	51	55	60
21	34	37	47	50	56	59	61
35	36	48	49	57	58	62	63

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3	8	12	17	25	30	41	43
9	11	18	24	31	40	44	53
10	19	23	32	39	45	52	54
20	22	33	38	46	51	55	60
21	34	37	47	50	56	59	61
35	36	48	49	57	58	62	63

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10	19	23	32	39	45	52	54
20	22	33	38	46	51	55	60
21	34	37	47	50	56	59	61
35	36	48	49	57	58	62	63

Fig. 3. JPEG's zigzag block scanning path and low-frequency subblocks for $N = 1, 2, 4$.

of a nonzero coefficient in $\{v(n)\}$ in a given block. We select $N = 1$ if $N_m = 0$, $N = 2$ if $N_m < 5$ and $v(3) = 0$, and $N = 4$ if $N_m < 14$ and $v(10) = 0$. If none of the conditions occur, we use a regular transform $N = 8$. The above conditions are trivial, except for the case $N = 4$, where we did not test all the data within a 4×4 subblock because it would require testing whether $N_m < 25$ plus checking if nine individual coefficients are nonzero. In this method, only three out of 16 coefficients are kept "outside" the 4×4 box by testing the end of the vector at the 14th instead of the 25th element. Tests show that the proposed simplification does not impact selection significantly, despite reducing computation.

Experiments were carried to compute how much time a real JPEG decoder would save by switching reduced transform approximations as we propose. Fig. 4 shows the frequency of occurrence of blocks in each class as a function of the compression ratio for several images. The relative complexity, as measured in decompression speed in a Sun Ultra Sparc architecture machine, is also shown in Fig. 4. The overall adaptive decoder is typically more than twice as fast as the normal decoder. In our experiments, the adaptive decoder did not produce any significant alteration in the image as compared to the normal JPEG decoder.

B. Encoder Adaptation

The decoder adaptation is more trivial since the data are readily available and need to be decompressed anyway. When compressing the image, if all the coefficients are computed and available, there is no need to use any reduced transform or coder. We have to estimate if there will be nonzero coefficients outside the boxes shown in Fig. 3, but without adding significant complexity. Otherwise it would be wiser to spend the extra computation to perform the full DCT.

Forward adaptation means that the analyzer should find the smallest N for a given block without losing high-frequency information. We propose to use hierarchical vector quantization (HVQ) as the data analyzer [12], [13]. HVQ is based on lookup tables (LUTs) and can easily map an 8×8 image block into a codeword with only six levels of LUT (63 LUT). As in any VQ

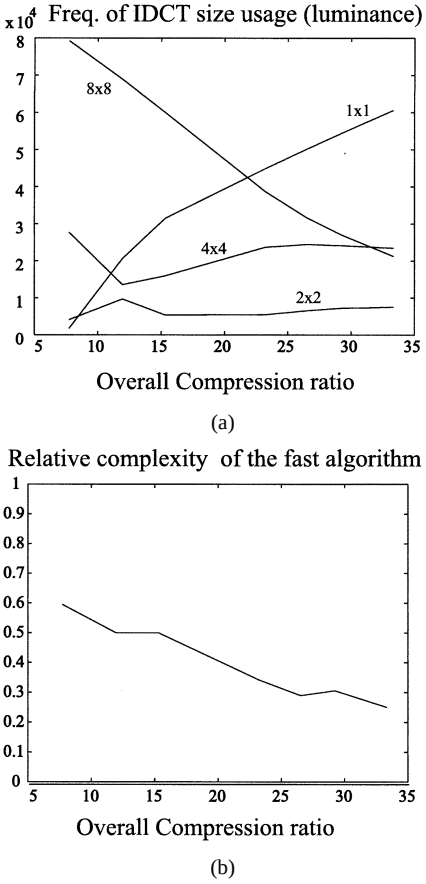

Fig. 4. Top: typical frequency of reduced inverse DCT size usage in JPEG decompression. Bottom: relative complexity of the proposed algorithm compared to normal JPEG decompression.

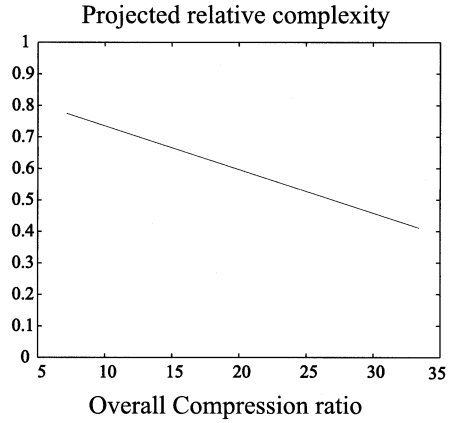

Fig. 5. Projected relative complexity of the proposed system which is based on an HVQ analyzer and multiple transforms in JPEG. The complexity is relative to standard JPEG coding of 8×8 blocks. It includes the HVQ analyzer and the compression steps.

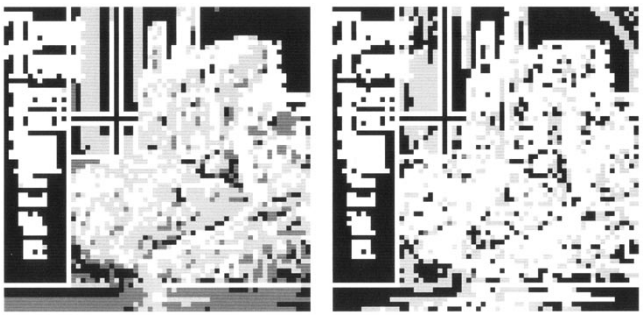

Fig. 6. Comparison between actual and estimated maps of reduced transforms. From black to white: $N = 1, 2, 4, 8$. (a) Actual and (b) estimated via HVQ ($Q = 3Q_d$ in both cases).

system, this codeword maps to a representative block which is supposed to approximate the input data. Like in the HVQ-JPEG case [14], we can use HVQ and map the output codeword to something else than a reconstruction block. In our case, the output codeword is mapped directly to a number between 1 and L indicating which coder should be used for the input block.

The LUT design is simple. The HVQ steps are designed using standard HVQ techniques. The mapping from codewords to encoder indices is done by correlating the HVQ output to a classifier's output for several images [15]. For each block and for a given quantizer table, the classifier design decides which is the smallest N such that the $N \times N$ lower frequency subblock contains all the non zero coefficients. The choice of N and the HVQ output for every block are correlated. At the end of training, each HVQ codeword is associated with the encoder selected by the classifier in the majority of the blocks in which such a codeword was produced.

The projected relative complexity of the proposed system is shown in Fig. 5. This estimation includes the HVQ analyzer and the JPEG compression components other than the DCT (quantization, variable-length coding, etc.). We use the term "estimated," instead of "measured," simply because we have not yet integrated the HVQ system with the JPEG one. Hence, we were forced to record time independently for each part. Nevertheless, the proposed system is to be twice as fast as JPEG for high compression ratios. Image quality, however, is not granted. HVQ is far from being a perfect representation of the input system. For 8×8 blocks we used six stages of 10-b codewords and yet the approximation is very rough. As a result, the analyzer may misjudge the input data. To minimize error visibility it is a good idea to be conservative, i.e., bias toward the slower coder in the HVQ mapping design phase. A comparison between actual and estimated block classification maps is carried in Fig. 6. In that figure dark regions mark the blocks where only the DC is computed $(N = 1)$. Lighter regions indicate blocks where $N = 2$, 4 or $N = 8$, for white pixels. It assumes a quantizer table $Q = 3Q_D$ (Q_d is JPEG's default quantizer table [1]).

The classification estimation errors are generally acceptable, mainly for high compression ratios. Fig. 7 shows objective evaluations comparing the proposed system with regular JPEG. It shows the peak signal-to-noise ratio (PSNR) related to the compression ratio (or bit rate) for two examples. It also shows the average PSNR difference between methods for several images. The proposed fast method with an HVQ-based analyzer is typically comparable to the regular compression method for high compression scenarios. As the compression ratio decreases, the proposed system yields images with lower relative quality. In any case, the decrease in objective performance is typically less than 0.7 dB for the bit rates of interest. Fig. 8 shows decompressed versions of image "mixed" after compression to a bi-

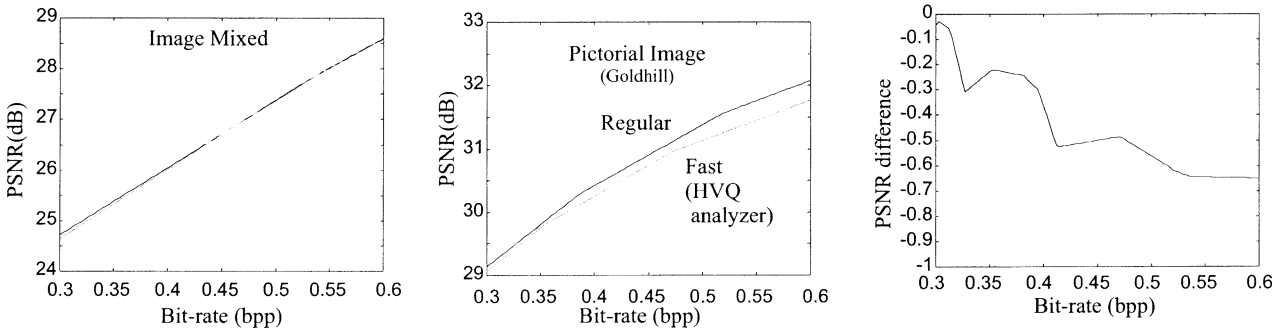

Fig. 7. Compression results for both regular JPEG and the proposed system (using an HVQ analyzer). Average PSNR difference computed using five images.

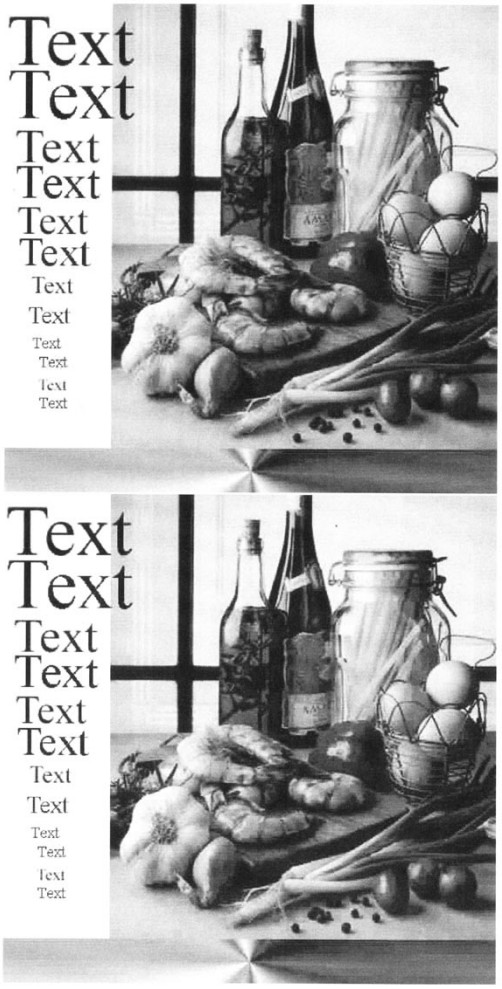

Fig. 8. Image "mixed" after compression to 0.52 b/pixel. Top: regular. Bottom: using proposed HVQ-analyzer-based system.

trate of 0.52 b/pixel. Both images were decompressed at a PSNR around 27.6 dB.

IV. Conclusion

Approximations to the DCT and their enabling algorithms were proposed for use in image compression in order to save the overall compression computation. They are suitable to JPEG and MPEG in high compression ratio modes. The need for high compression is to mask the effects of the approximation which can typically halve the overall computation for low bit rates and where JPEG/MPEG compression of the data blocks is already discarding too much visible information. In other words, savings come from not computing information that is not encoded. Multiple reduced transforms and coders are employed and coders are selected according to the results of an analysis of the input block. Such an analysis is performed very quickly via an LUT-based method derived from HVQ. The method was shown to be efficient to substitute the DCT in JPEG for low bit rates.

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