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Compression of signs of DCT coefficients for additional lossless compression of JPEG images

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Abstract

One of the main approaches to additional lossless compression of JPEG images is decoding of quantized values of discrete cosine transform (DCT) coefficients and further more effective recompression of the coefficients. Values of amplitudes of DCT coefficients are highly correlated and it is possible to effectively compress them. At the same time, signs of DCT coefficients, which occupy up to 20% of compressed image, are often considered unpredictable. In the paper, a new and effective method for compression of signs of quantized DCT coefficients is proposed. The proposed method takes into account both correlation between DCT coefficients of the same block and correlation between DCT coefficients of neighbor blocks. For each of 64 DCT coefficients, positions of 3 reference coefficients inside the block are determined and stored in the compressed file. Four reference coefficients with fixed positions are used from the neighbor blocks. For all reference coefficients, 15 frequency models to predict signs of a given coefficient are used. All 7 probabilities (that the sign is negative) are mixed by logistic mixing. For test set of JPEG images, we show that the proposed method allows compressing signs of DCT coefficients by 1.1 … 1.3 times, significantly outperforming nearest analogues.

Keywords: JPEG, JPEG additional compression, discrete cosine transform, sign compression

Introduction

JPEG standard [1], proposed in 1992, is still the most widespread and used method of image compression. Each day a huge amount of JPEG images is generated by smartphones and digital cameras, transmitted through digital channels to cloud databases, social networks, and saved on different data storage devices. Every day billions of JPEG images are downloaded from Internet while browsing the web. Therefore, a task of decreasing the size of JPEG images by additional lossless compression is very actual.

During the time elapsed from introducing JPEG standard, many more effective lossy image compression methods have been proposed [2-6]. However, a peculiarity of the task of additional compression of JPEG images is that any additional lossless are not allowed. It is not possible to decode JPEG images and just recompress it by a more effective method, e.g. JPEG2000 [2].

Therefore, a task of additional lossless compression of JPEG images is, actually, a task of more effective compression of quantized DCT coefficients of 8x8 blocks of images.

In [7], a review of methods of JPEG image lossless compression is given. The best of these methods, PAQ8 [8] and Stuffit [9], provide additional compression ratio at the level 1.2 … 1.25. Stuffit decodes a JPEG image to quantized DCT coefficients and decompresses it while PAQ8 predicts values of bites of Huffman codes in a JPEG image.

In [10], a method using recursive group coding [11] for compression of quantized DCT coefficients is described. The method having low computational complexity provides an additional compression of DCT coefficients by 5-10%.

A method proposed in [12] also operates with the decoded quantized DCT coefficients and uses the method described in [13] for their recompression. According to this method, signs and amplitudes of DCT coefficients are coded separately.

Compression of signs of DCT coefficients is carried out in many effective methods of lossy image compression, based on DCT, e.g. in ADCT coder [3]. As it was shown in [3], the signs of DCT coefficients occupy up to 20% of the size of a compressed image. However, a method of signs' compression proposed in [3] provides low compression ratios (on average, about 5%). For others methods, compression ratios are even smaller [14] or signs are not compressed (just stored).

The goal of this paper is to design an effective method of compression of signs of DCT coefficients of blocks of JPEG images. The main idea is a usage of signs prediction values of already coded coefficients of a current and neighbor blocks. A logistic mixing is applied to combine these particular predictions.

Description of the proposed method

We propose to compress signs of DCT coefficients after compression of their amplitudes.

For a prediction of the sign of a given DCT coefficient, seven reference DCT coefficients are used: three inside of the block and four in the neighbor blocks (Figure 1).

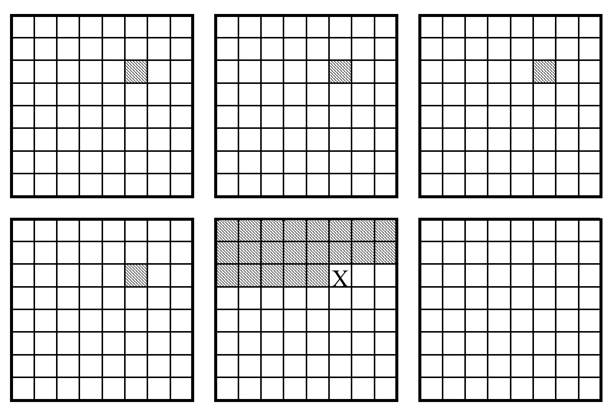

Fig. 1. Positions of DCT coefficients which can be used as the reference coefficients for a prediction of sign of coded DCT coefficient (its position is denoted as "X") are shaded

Let $I_{n,m}(i,j)$ be a value of DCT coefficient, where i, j are indices of the coefficients in an image block (i = 1...8, j = 1...8), n, m are positions (row and column) of the block in the image.
To predict and code the sign of the DCT coefficient $I_{n,m}(i,j)$, values of four coefficients of neighbor blocks are used: $I_{n-1,m-1}(i,j)$, $I_{n-1,m}(i,j)$, $I_{n-1,m+1}(i,j)$ and $I_{n,m-1}(i,j)$. In this way positions of four reference coefficients in the neighbor blocks are the same as the position of the coded coefficient $I_{n,m}(i,j)$.

Positions of three reference coefficients inside the coded block depend on the content of the coded image and are pre-selected from a shaded area (see Fig. 1) taking into account their correlation to the coded coefficient. Positions of these selected coefficients are stored in the compressed image. All such stored positions take in total no more than 8 x 8 x 3 = 192 bytes in the compressed file.

Thus, seven reference DCT coefficients $\{I^r_1, I^r_2, ..., I^r_7\}$ are simultaneously used for prediction and coding of the sign of DCT coefficient $I_{n,m}(i,j)$.

There are 15 frequency models associated to each of 7 reference coefficients.

The proposed method of compression of sign of a given DCT coefficient consists of the following steps.

1. For each of the 7 reference coefficients, according to the coefficient value the index of the corresponding frequency model is determined (see Table 1).
2. For each of the 7 frequency models, the probability that the predicted sign is negative is calculated.
3. The calculated probabilities are mixed into a one value using logistic mixing [7].
4. The obtained integral probability is passed to the binary arithmetical coder for compression of the sign.
5. Counters of all used frequency models are corrected according to true value of the sign.

Let us describe in details the prediction of sign of $I_{n,m}(i,j)$ for given reference coefficient I^o_k.

Each I^o_k value corresponds to one frequency model (see Table 1). Let F_{ijkt} denotes frequency model, where i and j are positions of predicted coefficient $I_{n,m}(i,j)$, k=1...7 is an index of the reference coefficient I^o_k, t=1...15 is an index of frequency model obtained from Table 1 by the value of I^o_k.

There are 64 combinations of i and j indices. Therefore, the total number of frequency models used in the proposed method is equal to 64 x 7 x 15 = 6720, which is acceptable since it does not require an extensive memory usage.

Each F_{ijkt} is an array containing two counters. $F_{ijkt}(1)$ is the number of already coded negative $I_{n,m}(i,j)$ for the frequency model. $F_{ijkt}(2)$ is the number of already coded positive $I_{n,m}(i,j)$. Before starting of coding, both counters are initialized by the unity values.

For seven reference coefficients $\{I^o_1, I^o_2, ..., I^o_7\}$, indexes of seven frequency models $\{F_{ij1t}, F_{ij2t}, ..., F_{ij7t}\}$ are obtained using Table 1.

Then, for each model P_k is calculated:

$$P_k = \frac{F_{ijkt}(1)}{F_{ijkt}(1) + F_{ijkt}(2)}, \qquad (1)$$

where P_k is a probability of the negative value of $I_{n,m}(i,j)$ for these values of I^o_k.

After calculation of all P_k, their values are mixed by logistic mixing [7] in accordance to the following scheme.

Table 1. Calculation of index of frequency model for given I^o_k

Value of reference coefficient I^o_k	Frequency model
≤ -64	1
-63 ... -32	2
-31 ... -16	3
-15 ... -8	4
-7 ... -4	5
-3 ... -2	6
-1	7
0	8
1	9
2 ... 3	10
4 ... 7	11
8 ... 15	12
16 ... 31	13
32 ... 63	14
≥ 64	15

Let w_{ijk} denote the weight of a k-th reference coefficient for a prediction of $I_{n,m}(i,j)$. In that case, an integral probability P^{int} is calculated as

$$P^{int} = \delta\left(\sum_{k=1}^{7} w_{ijk}\lambda(P_k)\right),$$
$$\lambda(P) = \ln\left(\frac{P}{1-P}\right),\ \delta(x) = \frac{1}{1+e^{-x}}. \qquad (2)$$

After coding of the sign of $I_{n,m}(i,j)$, values of w_{ijk} are adaptively corrected using the following equation:

$$w_{ijk} = w_{ijk} + \varepsilon(y - P^{int})\lambda(P_k), \qquad (3)$$

where y = 1, if the sign of $I_{n,m}(i,j)$ is negative, y = 0, if the sign is positive, ε is a learning rate equal to 0.01 [7].

Before coding is started, values of w_{ijk} are initialized by unities. Besides, when the condition $(i=1 \wedge j<4)$ is true, we propose to initialize w_{ijk} by the following values: {1, 1, 1, 1, 0.25, 0.25, 0.25}. Here, the first four values correspond to I^o_k from the neighbor blocks and three last values correspond to I^o_k from the coded block. If the condition $(i>2 \wedge j>2 \vee i>7 \vee j>7)$ is true, we propose to initialize w_{ijk} by the following values: {0.25, 0.25, 0.25, 0.25, 1, 1, 1}. It allows to accelerate weights adaptation and, consequently, to increase prediction accuracy.

Comparative analysis

For a verification of the proposed method of prediction of sign by similar coefficients (PSSC), a test set of 12 JPEG images (see Figure 2) is used. This set contains test images with different characteristics (textures, homogeneous regions, fine details, sharp edges) produced by different digital cameras which may have different image pre-processing chains.

Table 2 for each test image contains the following information: model of the digital camera, size of the JPEG image, number of non-zero DCT coefficients (signs of these coefficients should be predicted and compressed) and the percentage of memory occupied by signs in the compressed JPEG image.

Fig. 2. Test image set

One can see that the signs of DCT coefficients take from 10% to 15% of JPEG image size. Therefore, better compression of these signs is reasonable.

In the comparative analysis, in the paper a method of sign compression described in [3] is used.

Table 2. Characteristics of test images

#	Model of digital camera	File size, Mb	Number of non-zero DCT coefficients	Percentage of signs in compressed image, %
1	Canon EOS-1D X	8.76	11211868	15.6
2	Canon EOS-40D	7.442	9014262	14.44
3	Casio EX-FH100	5.462	6204274	13.54
4	Nikon D810	1.487	1730082	13.87
5	Nikon Df	1.475	1556391	12.58
6	Olympus C765UZ	3.696	3541823	11.42
7	Olympus E-500	5.214	4333982	9.91
8	Olympus XZ-2	4.832	4595926	11.34
9	Olympus XZ-2	6.279	5437935	10.32
10	Panasonic DMC-ZS100	6.501	6403968	11.74
11	Panasonic Lumix-LX20	4.443	4422325	11.87
12	Sony NEX-5N	2.24	2139618	11.39

Table 3 contains results of compression of signs of test image "Railway station".

For each combination of indices ij of DCT coefficient $I_{n,m}(i,j)$, there are two values in Table: number of non-zero coefficients (coefficients with a sign) for this position for whole image (in thousands) and compression ratio (CR) for these coefficients provided by the proposed PSSC method.

Bottom line of Table contains CR values for all signs of the test image.

Table 3. Results of compression of signs of DCT coefficients for the test image "Railway station"

	1	2	3	4	5	6	7	8
1	-	175 1.12	167 1.10	173 1.13	146 1.38	146 1.31	70 1.72	44 2.31
2	175 1.16	174 1.04	167 1.06	148 1.09	116 1.20	78 1.16	65 1.23	46 1.36
3	168 1.12	167 1.06	156 1.08	119 1.07	72 1.20	34 1.31	27 1.20	20 1.12
4	173 1.19	146 1.10	118 1.08	132 1.08	105 1.09	8.6 1.12	2.2 1.59	7.3 1.08
5	142 1.45	108 1.21	68 1.22	104 1.08	59 2.99	4.5 1.15	1.0 1.22	0.7 0.96
6	148 1.29	74 1.11	37 1.21	85 1.13	6.4 1.36	2.7 1.46	0.4 0.95	0.4 0.97
7	78 2.21	62 1.60	9.3 1.41	2.8 1.44	1.1 1.23	0.4 1.04	0.5 0.91	0.9 0.97
8	53 2.42	6.7 1.40	5.7 1.40	1.6 1.23	1.0 1.26	0.6 1.68	2.0 2.29	0.3 1.29
Compression ratio for all signs of the image: 1.196								

As it is seen from data in Table 3, PSSC provides effective compression of signs both for low frequency and high frequency DCT coefficients (that have large indices).

Tables 4 and 5 contain results of signs' compression for the test images "Signpost" and "Dogs".

It is seen that for these test images the proposed PSSC method also is able to effectively compress signs of low frequency coefficients as well as signs of high frequency DCT coefficients.

Table 4. Results of compression of signs of DCT coefficients for the test image "Signpost"

	1	2	3	4	5	6	7	8
1	-	179 1.07	174 1.06	175 1.08	155 1.40	155 1.57	100 1.95	68 2.49
2	179 1.09	178 1.10	173 1.09	158 1.08	138 1.41	109 1.68	100 1.78	70 2.00
3	173 1.08	172 1.08	164 1.08	137 1.05	107 1.32	70 1.42	60 1.52	32 1.56
4	174 1.08	157 1.08	137 1.06	146 1.03	127 1.12	29 1.18	6 1.93	9 1.21
5	155 1.49	136 1.47	106 1.31	126 1.11	77 1.69	12 1.22	2 1.20	0.8 0.94
6	156 1.50	105 1.56	72 1.38	105 1.08	17 1.18	5 1.32	0.5 1.04	0.4 0.93
7	104 2.45	99 2.16	34 1.94	8 2.21	3 1.59	0.5 1.22	0.6 0.99	0.9 0.96
8	75 2.82	20 4.09	13 2.47	2 1.45	1.1 1.21	0.6 1.35	2 1.94	0.3 1.21
Compression ratio for all signs of the image: 1.272								

Table 5. Results of compression of signs of DCT coefficients for the test image "Dogs"

	1	2	3	4	5	6	7	8
1	-	121 1.10	118 1.04	115 1.04	111 1.09	87 1.04	80 1.04	49 1.06
2	121 1.16	119 1.06	117 1.04	113 1.01	105 1.04	71 1.05	62 1.06	44 1.07
3	119 1.08	117 1.11	115 1.09	112 1.04	83 1.05	66 1.04	56 1.06	37 1.07
4	116 1.06	115 1.09	113 1.09	107 1.04	80 1.05	49 1.06	37 1.11	30 1.02
5	114 1.06	112 1.05	107 1.05	71 1.11	73 1.05	24 2.78	17 2.38	20 1.45
6	110 1.09	105 1.15	68 1.45	60 1.79	38 2.35	21 3.15	17 2.88	16 2.60
7	83 1.11	63 1.40	45 2.12	36 2.16	15 2.21	15 2.80	14 2.62	15 2.06
8	49 1.05	29 2.10	23 2.52	18 2.36	8 1.34	14 2.24	9 1.61	12 2.28
Compression ratio for all signs of the image: 1.141								

Let us show the necessity of simultaneous usage of both group of reference coefficients: from neighbor blocks and from the coded block.

Table 6 contains results of compression of signs of the same test image, but with prediction using only four reference I^o_k from neighbor blocks.

Comparison of data in Tables 3 and 6 allows confirming the necessity to take into account reference I^o_k from coded blocks. It is well seen that a prediction only by I^o_k of neighbor blocks is effective only for low frequency DCT coefficients (first row and first column of Table 4). For an effective compression of signs of high frequency coefficients such a prediction is not enough.

Table 7 contains results of compression of signs of the same test image, but with a prediction only using three reference I^o_k from currently coded block.

Table 6. Results of compression of signs of DCT coefficients for the test image "Railway station" with taking into account only reference coefficients of neighbor blocks

	1	2	3	4	5	6	7	8
1	-	1.12	1.10	1.13	1.36	1.19	1.41	1.49
2	1.16	1.03	1.04	1.04	1.15	1.12	1.20	1.33
3	1.12	1.04	1.01	1.00	1.11	1.00	1.03	1.01
4	1.18	1.04	1.01	1.01	1.03	0.99	1.08	0.99
5	1.42	1.15	1.11	1.04	2.90	1.01	0.98	0.92
6	1.27	1.06	1.05	1.11	1.32	1.18	0.84	0.79
7	1.51	1.07	1.03	1.10	1.04	0.86	0.85	0.94
8	1.53	1.09	1.23	1.08	1.11	1.23	2.02	0.85
Compression ratio for all signs of the image: 1.133								

Table 7. Results of compression of signs of DCT coefficients for the test image "Railway station" with taking into account only reference coefficients of coded block

	1	2	3	4	5	6	7	8
1	-	1.00	1.00	1.01	1.08	1.17	1.41	2.03
2	1.00	1.00	1.02	1.05	1.06	1.13	1.18	1.34
3	1.00	1.02	1.06	1.07	1.10	1.31	1.18	1.12
4	1.00	1.06	1.08	1.08	1.06	1.12	1.54	1.08
5	1.09	1.07	1.12	1.05	2.97	1.13	1.24	0.97
6	1.04	1.07	1.18	1.13	1.33	1.45	0.97	0.99
7	1.67	1.56	1.41	1.41	1.22	1.08	0.93	0.99
8	1.97	1.38	1.39	1.22	1.24	1.59	2.31	1.26
Compression ratio for all signs of the image: 1.097								

From the data in Table 7, one can see that the use in prediction of only reference coefficients from the coded block is not effective enough for compressing signs of low frequency coefficients, but is effective for prediction and compression of signs of mid frequency and high frequency coefficients.

Thus, joint prediction based on reference coefficients from neighbor blocks as well as reference coefficients from the coded block is reasonable because these coefficients complement each other.

A comparative analysis of the integral CR (for all signs of an image) is carried out in comparison with a method of signs compression used in ADCT coder [3]. The ADCT coder for several years after its design has provided the best compression ratio (for the fixed values of peak signal to noise ratio) in scientific literature.

Table 8 contains the results of compression of signs of all test images. As it is seen from this Table, compression ratio (CR) for PSSC is higher than that for ADCT for all test images.

For almost half of the test set, in particular, for the test images Floors, Museum, Radio, Snail, Asphalt, the method ADCT is ineffective providing CR not exceeding 1.01. At the same time, the proposed PSSC is able to compress these signs with CR = 1.08…1.25.

For several test images such as Signpost and Sunset, the method in ADCT provides good CR = 1.12…1.18. However, for these images, PSSC provides considerably better compression (CR = 1.27 … 1.29).

Taking into account that signs, for example, for the test image Sunset, take 11% from the total size of compressed JPEG image, an additional compression of signs by 1.29 times allows to decrease JPEG file size by 3%.

Table 8. Comparison of compression effectiveness of signs of DCT coefficients for PSSC and ADCT

№	Image	Compression ratio	
		ADCT	PSSC
1	Tiger	1.041	1.132
2	Flowers	1.006	1.086
3	Metropolis	1.037	1.098
4	Museum	1.006	1.252
5	Radio	1.013	1.143
6	Snail	1.008	1.147
7	Dogs	1.024	1.141
8	Railway station	1.058	1.196
9	Signpost	1.119	1.272
10	Cloud	1.085	1.163
11	Asphalt	1.011	1.104
12	Sunset	1.179	1.293

Analysis of the proposed method shows that the signs of low-frequency coefficients are better predictable by reference coefficients of neighbor blocks. At the same time, signs of high-frequency coefficients are better predictable by reference coefficients of the coded block. The used logistic mixing of probabilities provides an effective soft switching between these predictions.

Conclusions

The research carried out in this paper shows that the signs of quantized DCT coefficients of JPEG images can be effectively predicted and compressed.

The proposed PSSC method provides compression of signs of DCT coefficients by 1.1 ... 1.3 times, significantly outperforming the method of compression used in the ADCT coder.

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