The improved algorithm of the high-capacity information embedding into the digital images discrete cosine transform domain

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Abstract

Methods of the steganography are characterized by such efficiency rates as invisibility, robustness and capacity. There is considered the maximum capacity support of the information embedding into the DCT-domain. It is investigated the known algorithm that realizes the adaptive information embedding into the digital images frequency domain. The adaptivity is reached due to the image partition into the unequal blocks using a quad-tree. There is received the improved modification of the algorithm based on the reference point variation in case of the image partition into the blocks. The received modification allows to provide the better invisibility at the same capacity.

Keywords: digital steganography; data hiding; digital images; DCT; optimization

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1. Introduction

Digital steganography is one of modern directions of the informational security. Methods of digital steganography are directed on the organization of safe secret information transmission and copyright protection of digital objects such as digital images and audio and video data [1]. Solution of the given problem is attained by embedding the additional information with different functions in digital objects. In the given paper digital images are considered as digital objects.

The methods and algorithms of digital steganography are characterized by the following indexes of embedding efficiency: invisibility, robustness and capacity. A separate steganographic algorithm cannot ensure the maximum values of all specified parameters. The ratio between them can be described by the scheme presented on fig. 1.

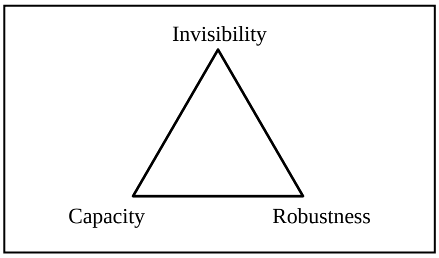

Fig. 1. Ratio between parameters of steganographic embedding efficiency.

The methods of digital steganography operating with digital images divide on two big groups on domain of data embedding: embedding in the spatial domain and embedding in the frequency domain. The pixel matrix of a digital image is named as the spatial domain, and the frequency domain is the matrix of values received from a digital image by application of any frequency transform. The given data are also named as coefficients of frequency transform. In digital image processing including the embedding information into images the following transforms are used: discrete Fourier transform (DFT), discrete cosine transform (DCT), Walsh-Hadamard transform (WHT), various versions of discrete wavelet transform (DWT).

In the present paper, providing the maximum capacity of embedding in the frequency domain of discrete cosine conversion at maintenance of comprehensible quality of the cover image is considered.

2. 2. Methods of embedding information in the frequency domain of digital images

There exist many algorithms where information embedding is carried out in the frequency domain of digital images. Frequency transforms associate the matrix of pixels of a digital image with the matrix of frequency coefficients. Frequency coefficients can be divided on significant (carrying the basic information of a source image), and insignificant (that can be discarded or modified without any noticeable distortions in the initial image) [2]. Therefore frequency embedding allows to better choose data elements which can be used for not noticeable recording of additional information.

Corresponding algorithms can be divided into algorithms of digital watermark embedding and algorithms of arbitrary message embedding. In the first case, the basic efficiency criterion of the algorithm is the stability of digital watermarks against cover image distortions; in the second case it is capacity and obscurity of embedding.

Let us note some research papers of last years.

Many algorithms of digital watermark embedding in digital images are based on DFT. The majority of such algorithms operate with elements of the amplitude Fourier spectrum.

In the algorithm presented in [3], space of hiding is formed of the middle frequency elements with values in the set range. For embedding of one bit of a digital watermark a pair of symmetrically allocated elements varies so that the difference between them accepts certain value depending on the embedded bit.

In paper [4] a digital watermark is formed as the amplitude Fourier spectrum with elements accepting values from set $\{0,1\}$. Significant elements form a circumference in the area of middle frequencies. It ensures stability in case of geometry attack like "turn of image".

In [5] for formation of the binary digital watermark with circle symmetry, log-polar mapping is used. When being embedded those elements of the peak Fourier spectrum of the digital image that correspond to elements of the digital watermark with values 1 are converted by averaging over neighborhood 3×3 with multiplication by the coefficient of amplification.

In [6] an adaptive algorithm of digital watermark embedding in the DCT-domain is presented. Adaptability of the given algorithm consists in usage of genetic algorithm to choose the optimal embedding order of digital watermark parts in cover image blocks.

The algorithm presented in [7] and based on DFT is designed for embedding arbitrary messages. In the given algorithm, DFT is not applied to the whole image but to blocks of size 8×8 pixels. 16 bits of the secret message are built in the phase spectrum of each block. Embedding is carried out by means of modified differential phase-shift keying. For this purpose, phase values of block pairs are compared and differences between them are calculated. Certain intervals of differential values correspond to zero and on-bits of the secret message. To determine the necessary differences between phase values of current and previous blocks, the modifications to phase values of the current block are made.

In article [8] the algorithm which can be used for embedding both arbitrary messages and digital watermarks is presented. The given algorithm is based on DWT. Embedding area is the middle-frequency sub-band LH2 received after two iterations of DWT. One bit of the secret message is built in the block from *k* DWT-coefficients. Embedding consists in a modification of the block coefficient energy by means of matrix operations. To improve the quality of embedding, authors of the given paper apply optimization methods for matrix functions. The modification of value *k* changes the ratio between capacity and robustness. At the increase of *k*, the built-in message accepts properties of a digital watermark.

In paper [9] embedding is carried out in the WHT frequency domain. For this purpose the image is divided into blocks by 4×4 pixels; and WHT is applied to each block. The algorithm of embedding is built using a linear predictor function. Values of AC-coefficients of WHT of each block are predicted on the basis of DC-coefficient values of 8 adjacent blocks. The message bits are built in prediction errors according to the LSB method. To determine the weighting coefficients of the linear predictor function the neural network is used.

A series of publications [10–12] represents results of research directed on reaching the maximum capacity of embedding in the frequency domain of discrete cosine transform.

In paper [10], the cover image is divided into non-overlapping blocks by the size of $m \times m$ pixels; DCT is applied to each block. For embedding, a part of the DCT-coefficient block is used, that forms a square in the right lower angle. This square corresponds to the least significant high-frequency coefficients and has a different size for different blocks. The size of embedding area is defined by the quantization matrix. Embedding consists in replacement of DCT-coefficients in the area of embedding by elements of the secret message. The secret message is also a digital image; and pixels of this image are exposed to additional quantization before embedding.

The given approach is developed in papers [11, 12]. The algorithm presented in [11] represents a different method of the secret image processing before embedding it. In [12], the cover image is divided into homogeneous blocks of pixels having unequal size by using quad-tree, that allows to raise the efficiency of embedding.

The present paper develops the offered in [10–12] approaches to high-capacity embedding of information into the frequency domain of discrete cosine transform. In the following section of the paper a more detailed description of algorithm [12] is given; probable ways of its improvement are defined and a new more effective algorithm is offered.

3. New algorithm on the basis of the approach to high-capacity embedding of information into the frequency domain of discrete cosine transform

3.1. Adaptive algorithm of embedding using a quad-tree

Let's consider the QTAR embedding algorithm presented in article [12] in more details.

Input:

Square cover image I; secret image S; homogeneity threshold of block Th; minimum block size m; square matrix of quantization of a size 8×8 $\mathbf{Q}$; scale factor k.

Output:

Cover image containing a secret image I'.

Step 1. To execute recursive partition of each inhomogeneous square pixel block of the cover image into four equal sub-blocks. The cover image is taken as an initial block. The block partition stops if its size (the square side) is less or equal to m or if it is homogeneous. The block is recognized as inhomogeneous if the difference between the maximum and minimum values of pixels is higher than $255Th$ value.

Step 2. To execute the scaling of the secret image pixels by formula $\tilde{s}_i = {}^{k}\!/_{255}\, s_i$.

Step 3. For $j = \overline{1, N}$, where N — is amount of blocks in the quad-tree to execute as follows:

Step 3.1. To execute two-dimensional DCT of the *j*-th block of pixels of the size $m_j \times m_j$.

Step 3.2. To expand matrix $\mathbf{Q}$ to the extent of $m_j \times m_j$ using interpolation and to divide the DCT-coefficients of the block into elements of the given matrix with the subsequent round-off.

Step 3.3. To select a square area of the greatest possible size $n_j \times n_j$, consisting only of nulls in the right lower angle of each block of the quantized DCT-coefficients.

Step 3.4. In the initial block of DCT-coefficients (before quantization) to substitute area of embedding n_j^2 with pixels of modified secret image $\tilde{S}$.

Step 3.5. To execute inverse two-dimensional DCT.

Step 4. To return stego image I' and key sequence $(n_1, n_2, \ldots, n_N)$ and complete the algorithm.

To extract the secret image, it is necessary to repeat the partition of the cover image into blocks with a quad-tree, than apply DCT to blocks of pixels, and after that select the area of embedding in each block of DCT-coefficients with and to extract a part of embedded data from it. After reconstructing image from separate parts, it is necessary to execute an inverse scaling from segment [0, *k*] to [0, 255]. The pixels of the secret image are rebuilt inaccurately because of the round-offs originating during scaling, but these distortions do not lead to considerable loss of quality.

Fig. 2 shows the partition of image «Lenna» onto homogeneous blocks with a quad-tree and the selection of embedding areas.

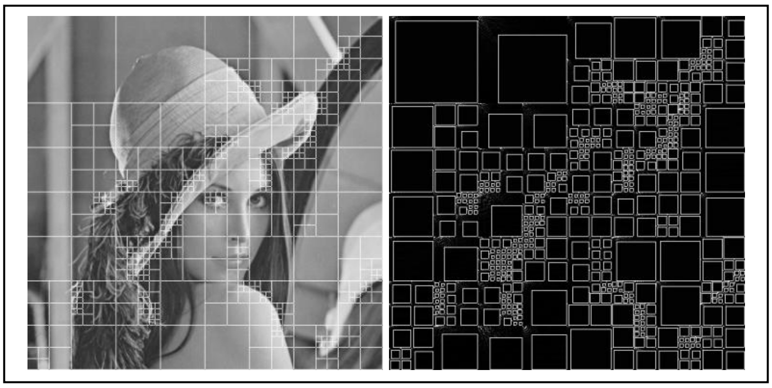

Fig. 2. Partition of the image “Lenna” on blocks (*Th* = 0,6; *m* = 8; *k* = 4,37).

3.2. Possible ways of QTAR algorithm improvement

In the QTAR algorithm the quad-tree construction starts with the cover image which is considered as an initial square block of pixels. Coordinates of the top left corner of the given initial block are named as an index point and designated as (x, y). In the initial algorithm the given point has coordinates $(0, 0)$ and cannot be changed. However, if the digital image is presented in the form of torus, for example as in cellular automata models [13], it is possible to choose any point of the cover image as an index point. The index point modification will change the form of the quad-tree and will affect the distribution of parts of the secret image on the cover image blocks. The example is shown on fig. 3. The index point is marked white.

Fig. 3. Partition of the image “Lenna” on blocks with the modified index point (*x* = 412; *y* = 412) (*Th* = 0,6; *m* = 8; *k* = 4,37).

Fig. 4 shows the modification of the quality indexes and embedding capacity after modification of the index point in the case of embedding the “Baboon” image into “F15” image. The embedding quality index is the peak signal-to-noise ratio (PSNR). The index of embedding capacity is the bits per pixel amount (BPP). In this case, the index point corresponds to PSNR value of 33,745 dB and BPP value of 7,387 by default. One can see that the index point modification allows to increase PSNR value at equal or comparable BPP value.

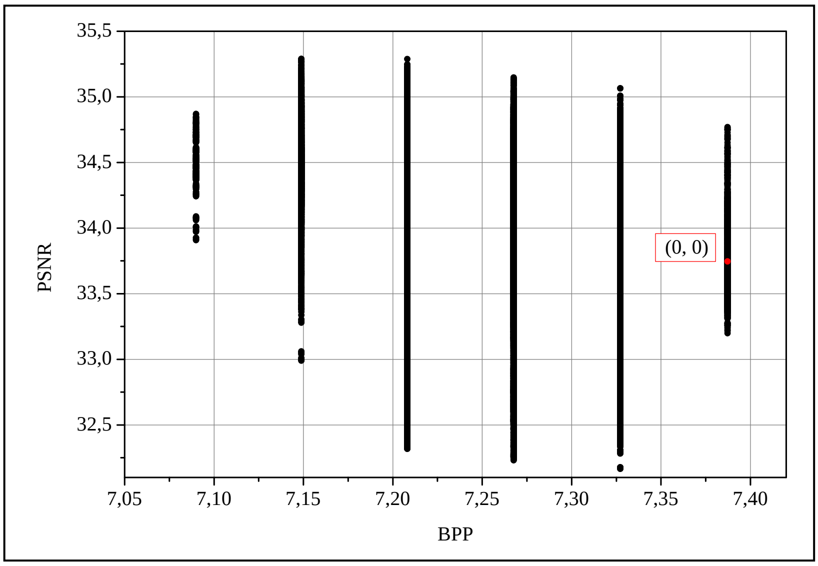

Fig. 4. Modification of PSNR and BPP at modification of the index point (*Th* = 0,4; *m* = 8).

The second possible approach to improvement of QTAR algorithm is connected to selecting of the threshold value. Since the brightness of an image makes essential impact on perception of the given image by human sight, in the present paper it is offered to introduce different threshold values for blocks of the image with different brightness. For this purpose, let us divide all brightness range of pixels on three equal sub-bands $[0, 255] = [0{,}85] \cup (85, 170] \cup (170, 255]$ define the threshold value of block homogeneity for each part and designate them as Th_1, Th_2, Th_3 accordingly.

Besides the fact that the given data along with the index point should influence efficiency of the embedding algorithm, they can also be used as an additional key element.

3.3. The offered improved algorithm

Exhaustive search of every possible value of an index point and homogeneity threshold of blocks is inconvenient, since it requires a great number of calculations. Therefore in the present research differential evolution (DE) is used for the solution of the given problem. It is the known metaheuristics widely used for solving the problems of optimization in various application areas, including digital steganography [14]. It allows to optimize sets of real heterogeneous parameters.

Since DE is a well-known optimization method, it is not described in the present article. Let us only mention that the DE algorithm operates with the following parameters: the size of population N, mutation coefficient F, probability of crossing over CR, number of calculations of object function K.

Object function is defined by the following formula:

$$f = \frac{PSNR - PSNR^{\text{QTAR}}}{PSNR^{\text{QTAR}}} + \frac{BPP - BPP^{\text{QTAR}}}{BPP^{\text{QTAR}}}, \qquad (1)$$

where $PSNR^{\text{QTAR}}$ and BPP^{QTAR} are values of efficiency indexes at embedding according to the initial QTAR algorithm.

Then the new algorithm of high-capacity embedding of the information in the frequency domain of discrete cosine transform of digital images on the basis of algorithm QTAR can be represented as follows:

Input:

Square cover image I; secret image S; minimal block size m; matrix of quantization of the size 8×8 $\mathbf{Q}$; scale factor k; parameters of DE algorithm.

Output:

Cover image containing the secret image I'.

Step 1. To execute the scaling of the secret image pixels by formula $\tilde{s}_i = {}^{k}\!/_{255}\, s_i$.

Step 2. To build in the secret image S into the cover image I being the QTAR algorithm. To record the received values of quality indexes and embedding capacity as $\text{PSNR}^{\text{QTAR}}$ and BPP^{QTAR}. To calculate the value of object function by formula (1) and to record it as $f^{\max}$.

Step 3. To generate N vectors of form $\mathbf{x}^i = (x, y, Th_1, Th_2, Th_3)$, $i = \overline{1, N}$.

Step 4. For $i = \overline{1, N}$ to execute the following:

Step 4.1. To represent the cover image in the form of a quad-tree consisting of M^i blocks of pixels, using the vector of parameters $\mathbf{x}^i = (x, y, Th_1, Th_2, Th_3)$.

Step 4.2. For $j = \overline{1, M^i}$ to execute the following:

Step 4.2.1. To execute the two-dimensional DCT of the *j*-th block of pixels with the size $m_j \times m_j$.

Step 4.2.2. To expand the matrix $\mathbf{Q}$ to the extent of $m_j \times m_j$ using interpolation; and to divide the DCT-coefficients of a block into elements of the given matrix with the subsequent round-off.

Step 4.2.3. To select a square area of the greatest possible size $n_j \times n_j$, consisting only of nulls in the right lower angle of each block of quantized DCT-coefficients.

Step 4.2.4. In the initial block of DCT-coefficients (before quantization) to substitute the area of embedding n_j^2 with pixels of the modified secret image $\tilde{S}$.

Step 4.2.5. To execute the inverse two-dimensional DCT.

Step 4.3. To calculate values of quality indexes and capacity of embedding PSNR^i and BPP^i. If $\mathrm{PSNR}^i < \mathrm{PSNR}^{\mathrm{QTAR}}$ or $\mathrm{BPP}^i < \mathrm{BPP}^{\mathrm{QTAR}}$, then it is necessary to assign $f^i = 0$, otherwise to calculate the value of object function f^i by formula (1).

Step 4.4. If $f^i > f^{\max}$, then to assign $f^{\max} = f^i$ and to record the vector $\mathbf{x}^i$ as the best solution $\mathbf{x}^{\mathrm{best}}$.

Step 5. To renew the population by rules of differential evolution.

Step 6. If the amount of evaluations of object function does not exceed K, then to pass to step 4. Otherwise to pass to step 7.

Step 7. To build in secret image S into cover image I using the vector of parameters $\mathbf{x}^{\mathrm{best}}$, then return stego image I' and key sequence $(n_1, n_2, \ldots, n_M, x, y, Th_1, Th_2, Th_3)$ and complete the algorithm.

In the following section of the present article, the results of computing experiments with the given algorithm and its comparison to the QTAR algorithm are presented.

4. Results of experiments and their discussion

Computing experiments with the QTAR algorithm and the offered algorithm were carried out on the test sampling including 19 grey-scale and 3 full-color images with the resolution of 512×512 of pixels. The given sampling was formed from base of images [15]. The examples of test images are shown on fig. 5.

Fig. 5. Examples of test images.

Table 1 shows the results of the efficiency estimation of our algorithm in comparison with the initial QTAR algorithm. For each image, the optimal parameters of embedding are specified, which were found by means of differential evolution. Parameters of differential evolution were set according to the guidelines presented in [16] for the optimization problem of dimensions 5. Last three table lines correspond to full-color images; the rest of the images are grey-scale.

One can see that in most cases our algorithm surpasses the QTAR algorithm and only on occasion shows comparable results. For example, it refers to images “Arctichare”, “Clouds”, “F15”. In those cases the proposed algorithm cannot reach substantial improvement. Also, if one parameter increases, other parameters decrease. It is possible to explain in the following way: the point by default $(0, 0)$ for the given images gives the solution that belongs to Pareto-frontier. For images “Cat”, “Peppers”, “Baboon” the proposed algorithm noticeably surpasses QTAR in terms of BPP at the comparable value of PSNR. But for the majority of images the proposed algorithm surpasses the QTAR algorithm in terms of both considered indexes. As a result, the maximum advantage of PSNR over the best value of BPP is 1,07 dB, and the maximum advantage of BPP over comparable value of PSNR is 1,1 bits, which is significant improvement.

Regarding the stability against steganalysis, the offered algorithm also surpasses the QTAR algorithm, since the embedding operation in both cases is the same, but additional parameters used by the offered algorithm increase the private key size.

Table 1. Comparison of the proposed algorithm and the QTAR algorithm

Image title	QTAR		Proposed algorithm					
	PSNR, dB	BPP	PSNR, dB	BPP	Index point	Th_1	Th_2	Th_3
Arctichare	41,63	**5,85**	**44,02**	4,02	(184, 40)	0,48	0,66	0,94
Baboon	32,99	3,02	**33,00**	**4,11**	(129, 88)	0,97	0,23	0,21
Barbara	26,86	5,03	**27,06**	**5,11**	(455, 448)	0,34	0,16	0,12
Blonde	32,01	5,21	**32,09**	**5,36**	(497, 317)	0,11	0,24	0,16
Boat	**33,11**	4,88	**33,11**	**4,98**	(448, 313)	0,23	0,18	0,84
Cameraman	37,58	5,53	**37,72**	**5,62**	(335, 402)	0,10	0,05	0,44
Cat	34,20	4,34	**35,27**	**4,38**	(192, 128)	0,16	0,89	0,34
Clouds	37,53	**5,64**	**38,46**	4,57	(432, 123)	0,78	0,84	0,07
Darkhair	37,16	5,94	**37,21**	**5,99**	(284, 256)	0,14	0,65	0,47
Fruits	34,59	5,16	**34,61**	**5,31**	(160, 178)	0,89	0,12	0,43
House	42,37	5,80	**42,76**	**5,80**	(384, 256)	0,90	0,40	0,20
Jellyfish	36,92	5,80	**37,31**	**6,26**	(480, 384)	0,07	0,79	0,94
Jetplane	36,15	5,03	**36,23**	**5,36**	(124, 208)	0,39	0,60	0,11
Lake	33,86	4,67	**33,92**	**4,83**	(5, 275)	0,00	0,54	0,14
Livingroom	34,51	4,52	**34,60**	**4,74**	(455, 185)	0,08	0,18	0,72
Peppers	33,99	4,33	**34,00**	**5,43**	(402, 234)	0,63	0,18	0,15
Pirate	33,24	4,81	**33,25**	**4,88**	(131, 112)	0,20	0,38	0,52
Sails	30,62	3,85	**30,64**	**3,89**	(208, 446)	0,14	0,35	0,69
Walkbridge	31,16	3,85	**31,19**	**3,89**	(288, 152)	0,53	0,04	0,16
F15	38,59	**17,64**	**39,69**	14,65	(193, 353)	0,42	0,70	0,84
Lenna	33,37	16,00	**33,39**	**16,69**	(191, 384)	0,26	0,21	0,22
Tiger	36,26	17,01	**36,76**	**17,72**	(263, 304)	0,93	0,72	0,07

5. Conclusion

The given paper presents the new algorithm of high-capacity embedding of the information into the frequency domain of discrete cosine transform received on the basis of known (existing) QTAR algorithm. A distinctive feature of the offered algorithm is an approach to representation of the cover image in the form of a quad-tree of homogeneous blocks of pixels. Besides, the optimization by means of differential evolution is applied. Computing experiments showed that the offered algorithm has higher efficiency in terms of quality and embedding capacity.

Development of the given paper will consist in the search of new approaches to partition of the image-container into homogeneous blocks of pixels and synthesis of new algorithms of embedding.

Besides, the transfer of the initial approach to the achievement of high-capacity embedding on other transforms applied in digital image processing, except discrete cosine transform, is interesting.

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