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TATRA
MOUNTAINS
Mathematical Publications

DOI: 10.1515/tmmp-2016-0034
Tatra Mt. Math. Publ. **67** (2016), 99–116

STEGANALYSIS OF STEGOSTORAGE LIBRARY

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ABSTRACT. The main goal of this research is the detection of the secret messages hidden in JPEG files, which were embedded by StegoStorage library. This tool allows the user to embed any type of information into a folder of images. Sequential, pseudo-random or Hamming code-based embedding into the least significant bit (LSB) of DCT coefficients is possible. It is possible to choose what fraction of capacity of the cover files are filled.

The aim of this contribution is to test the statistical LSB embedding model (modified weighted-stego analysis) for all modes of embedding which StegoStorage library offers, and for all cover files' capacities, respectively. Another goal is to implement a more appropriate type of steganalytic attack for Hamming codes and test it. For this purpose, the RS (Regular/Singular) steganalysis was selected.

The detectability of the LSB embedding model of sequential embedding is possible if the cover files are filled to at least one percent of capacity. In the case of pseudo-random embedding, the secret message can be detected if the cover files are filled to at least 10 % of their capacity. Hamming codes were undetectable using this type of an attack.

In the case of attack by RS steganalysis, another situation arose. When sequential or pseudo-random embeddings were used, the results indicated the detectability was possible if the cover files were filled up at least 5 percent of capacity. The capacity filling of 5 percent corresponds to 2.5 percent of DCT coefficient changes from the original media in the case of sequential embedding. This value, 2.5 %, is the threshold for the utilization of Hamming codes, too. Therefore, Hamming codes (7, 4), (15, 11) and (32, 26) indicated the detectability, because they exceeded that limit.

2010 Mathematics Subject Classification: 68P30, 94B05, 94A08.
Keywords: steganography, steganalysis, LSB embedding, JPEG, Hamming codes, statistical tests, detectors, StegoStorage.
This project is based upon work supported under the grants VEGA 1/0173/13 and VEGA 1/0529/13 and is co-funded by the EEA Grant SK06-IV-01-001 and the state budget of the Slovak Republic from the EEA Scholarship Programme Slovakia.

1. Introduction

Steganography is the art of hiding every trace of communication. In today's modern technology world, invisible ink and paper have been replaced by more adjustable and practical cover objects — digital files, such as images, audio, video or documents files. The simplest example of steganography is the use of electronic documents, which contain perceptually irrelevant or redundant information. This file can be then used as a cover medium to hide secret messages.

Using steganography, it is possible to transfer any type and form of information. This information may (but does not need to) be encrypted. It can be a message or, what can be worse for an ordinary user, it can be malware. Images can hide a large amount of malicious code that could be activated by a small Trojan horse. Currently, there are some sources which inform that the steganography has already been misused even by some terrorist groups [12]. Therefore, this issue seems to be very important to explore.

On the other side of steganography is its analysis - steganalysis. Steganalysis may have several objectives, which are the detection of steganography, the estimation of message length, and its extraction. Especially abroad, the steganalysis has recently gained more and more popularity in the media. In practical steganalysis, we can recognize several qualitatively different approaches, e.g., detection based on first-order statistics (histogram analysis), higher-order statistics (RS steganalysis), and special cases, such as JPEG compatibility steganalysis [11], etc. Currently, researches are devoted to the so-called rich models and game theory approach. Most of these attacks use the passive warden scenario, when the attacker does not modify the files in any way, is only an eavesdropper and files are intercepted.

The aim of this contribution is the detection of information possibly present in JPEG image files. Specifically, our goal is to detect any data, which were embedded by a system called StegoStorage [1]. StegoStorage system embeds information into the least significant bit of DCT coefficients, which can be sequential, pseudo-random but can also make use of the Hamming codes [1]. Our aim is to achieve the detectability of all possible embedding which are offered by this steganographic tool. We continue the research started in [13]. Our steganalytical algorithms were implemented in Python programming language using scientific tools such as NumPy or SciPy.

This contribution is divided into several sections. In section 2 and 3 there are some basic preliminaries and information about the analyzed library. In section 4, we present our implementation of WS analysis [3] in frequency domain of DCT coefficients and its results. Section 5 is devoted to the adaptation and results of RS analysis [3] for the domain of DCT coefficients, too. In the conclusion we summarize the results and outline directions for the future research.

2. Preliminaries

2.1. Steganographic terminology

Each steganographic communication system consists of an embedding algorithm and an extraction algorithm, which are usually specific to the particular steganographic tool [5]. Another integral part of such system are files that are used to transmit the information. Therefore, it is important to distinguish the file type in the concept of digital steganography. The original file, into which a secret message is embedded, is called the *cover* file and so it is slightly modified by the embedding algorithm. After the process of embedding, the *carrier* file is obtained. Therefore, the *carrier* file is a file with a hidden secret message. All these sets of files are part of the steganographic communication system. A steganographic scheme can be seen in Figure 1. Another important term in digital steganography is the *capacity* of the cover file. It is the maximum size of the secret message that can be inserted into the cover file. In the concept of JPEG steganography it has units of *bpac* (Bits Per non-zero AC DCT coefficients).

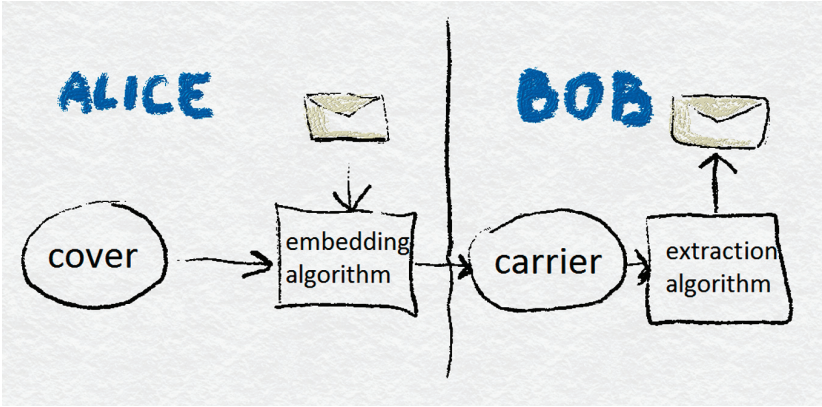

FIGURE 1. Steganographic communication scheme.

2.2. Terminology of image processing

JPEG (Joint Photographic Experts Group) is an international compression standard for grayscale and color images. The JPEG standard has two basic compression methods. The DCT-based method is designed for lossy compression, and the predictive method is designed for lossless compression [6]. We are interested in the lossy method, in [6] called baseline.

According to [6], JPEG encoding consists of the following steps:

***Color Space Conversion*:** is the transformation from RGB color model into a luminance-chrominance color space such as YCbCr. The reason is chrominance channels - Cb and Cr. They contain a lot of redundant information and can be easily subsampled without any significant effect on the resultant image quality. We are interested in luminance component Y only, because the secret message is embedded into it. The luminance value is counted as follows: $\mathrm{Y} = 0.299\,\mathrm{R} + 0.587\,\mathrm{G} + 0.114\,\mathrm{B}$.

***Downsampling*:** is the first information loss in the JPEG standard. It is based on the fact that the human eye seems to be more sensitive to the luminance than the chrominance. There are three basic color formats: $4:4:4$, $4:2:2$ and $4:2:0$.

***Discrete Cosine Transform*:** is the transformation of pixel values into the spatial frequencies - DCT coefficients. It is applied to 8×8 blocks of pixels. The mathematical definition of DCT is defined in [6]. After transformation, each 8×8 block consists of 64 DCT coefficients. The first coefficient is the DC component and the other 63 coefficients are AC components.

***Quantization*:** is the next compression process. Each of the 64 DCT coefficients are quantized, it means that each DCT coefficient is divided by the corresponding quantizer parameter in the quantization matrix and rounded to the nearest integer [6]. Then, each 8×8 block is reordered in a zig-zag order.

***Entropy Coding*:** is used for the lossless compresion of quantizated vectors. It utilizes the fact that quantized matrices contain a lot of zeros. Mostly, the Huffman coding is used.

3. StegoStorage library

StegoStorage was developed by Košdy in 2013 and its detailed description can be found in [1]. The most significant difference in comparison with other steganographic tools is that this system is able to insert a single message into multiple images. Three image formats are (so far) supported: JPEG, BMP and most resent, PNG. In this article, we focus our analysis on the JPEG format, because we regard it as the most popular. It is multiplatform, thus it works on Linux, OS X and Windows. Because the architecture of the StegoStorage is modular, it can be easily extended with the new embedding algorithms, coding techniques, permutation generators, etc. It is available at[1]. From the viewpoint of analysis, it is important that StegoStorage uses two types of permutations:

[1] https://github.com/MatusKysel/StegoDisk

(1) *global permutation* - provides global diffusion (spreads bytes of hidden storage among files),
(2) *local permutation* - permutation of LSB bits within one file (important against steganalysis).

This library makes use of the embedding into the least significant bit of DCT coefficients, which can be sequential, pseudo-random but can also make use of Hamming codes [9]. These codes are perfect linear codes, which minimize the number of changes in the carrier files, thereby complicate the detection. Also StegoStorage library allows users to fill any amount of cover medium capacity.

Let us explain the effects of inserting on a simple example. Let us have a database of 3 images. We want to fill 50 % of the cover files' capacity. In the case of sequential embedding, this message will be embedded into 2 images. On the other hand, in the case of enabled permutation, this message will be embedded into all images in our database.

4. Targeted weighted steganalysis

This section is in accordance with [13]. The key idea behind the process of Weighted Steganalysis (WS) is that the macroscopic cover properties can be estimated via the weight β that minimizes the Euclidean distance between the weighted carrier image and the cover image [3]. In practice, the steganalyst does not know the cover file so it has to be estimated from the carrier file itself using the calibration method [8], which we have also previously implemented. The most important part of this type of an attack is to design a proper mathematical model that describes the changes of the DCT coefficient histogram of the image after embedding a secret message. Unlike most applications of this type of an attack, we applied it to the frequency domain, because the StegoStorage embeds the secret message into the DCT coefficients, not to the pixels. Note that during the testing period we were embedding a pseudo-random data into the cover files.

We proceeded similarly to [7] and [10].

Let $h_{kl}(d)$ be the total number of AC DCT coefficients in the cover image corresponding to the frequency $(k, l) \in \mathbb{Z}$, $1 \leq k,\ l \leq 8$, whose value is equal to d, $d \in \{-2, -1, 2, 3\}$. The corresponding histogram values for the carrier will be denoted H_{kl}. Let us assume that the LSB embedding process changes n AC coefficients. The probability that a non-zero AC coefficient will be modified is $\beta = n/P$, where P is the total number of non-zero AC coefficients.

Because the selection of the coefficients is pseudorandom in the StegoStorage system (due to the utilization of pseudorandomly permuted coefficients in

Hamming coding embedding scheme), the expected values of the histograms H_{kl} of the stego image are

$$\begin{aligned} H_{kl}(d) &= (1-\beta)h_{kl}(d) + \beta h_{kl}(d+1), \text{for } d = 2m \text{ (even number)}, \\ H_{kl}(d) &= (1-\beta)h_{kl}(d) + \beta h_{kl}(d-1), \text{for } d = 2m+1 \text{ (odd number)}. \end{aligned} \tag{1}$$

This equation expresses the dependency of pairs of values, which originated from LSB embedding.

4.1. Results of sequential embedding

The results of the tests when sequential embedding was used and thus permutation and Hamming codes were disabled are presented in this section. It is possible to use the filling percentage to calculate the number of images into which the message was embedded, because the message was embedded into images in sequential order. Furthermore, because the message was embedded into sorted files, it is possible to determine the error types one and two.

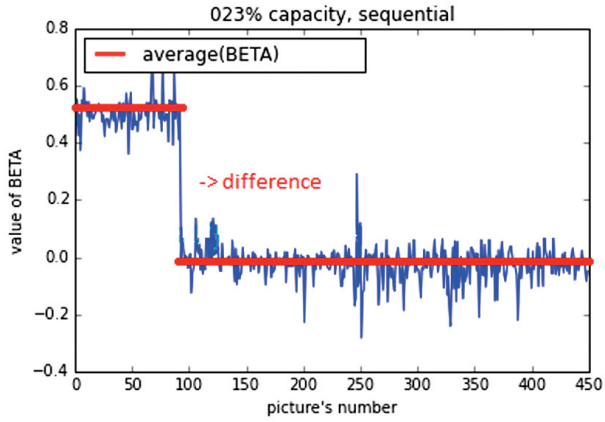

FIGURE 2. Values of β for each image from database, sequential embedding, 23 % capacity filling of the cover files, sorted.

Figure 3 shows the detectability depending on the amount of embedding. The X-axis shows the rate of capacity filling of the cover medium in percentage. The Y-axis shows the difference between the average value of β with message and the average value of β without message. An illustration of how the difference is determined can be seen in Figure 2. The X-axis shows the picture number in the database. The Y-axis shows the estimated value of the β parameter (the probability that the non-zero DCT coefficient will be modified).

On the left side at the top, there is a group of images in which the message was hidden. Note that detection is possible from the first percents of filling of the cover files.

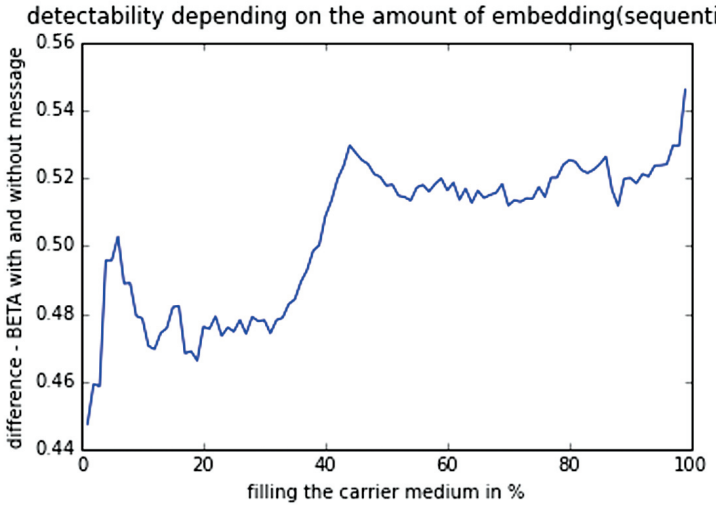

FIGURE 3. Detectability of sequential embedding.

4.2. Results of pseudo-random embedding

This part presents the results of embedding into the LSB of DCT coefficients using StegoStorage settings of permutation enabled and Hamming codes disabled. Figure 4 demonstrates the situation of the enabled permutation and filling the sixty percent of the capacity. The horizontal axis shows the picture number from the database. The vertical axis shows the value of the essential parameter-β. It should be noted that some groups of images with a different value of β than it was in the case of sequential embedding are not included.

The detectability of pseudo-random embedding is showed in Figure 5. It is worth mentioning that the X-axis shows the average value of β of the whole image database because the message is spread into all images. We may claim that from approximately 10 percent, the secret message can arguably be detected.

4.3. Results of Hamming codes

The purpose of using Hamming codes is to spread the hidden message in such a way that the number of modified DCT coefficients will be minimal. This ensures a lower likelihood of having the secret message detected [2].

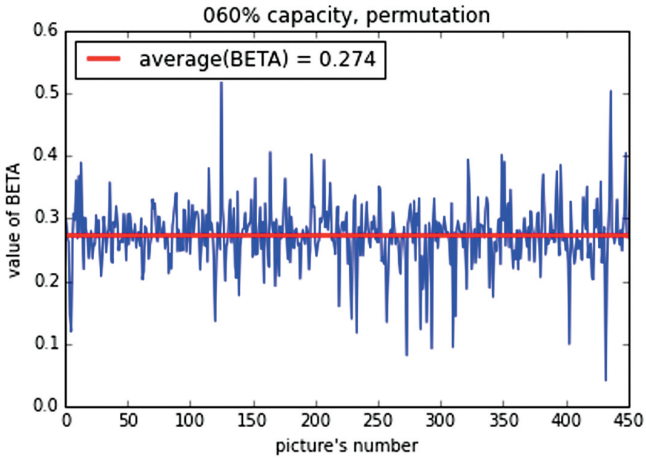

FIGURE 4. Values of β for each image from database, pseudo-random embedding, 60 % capacity filling of the cover files.

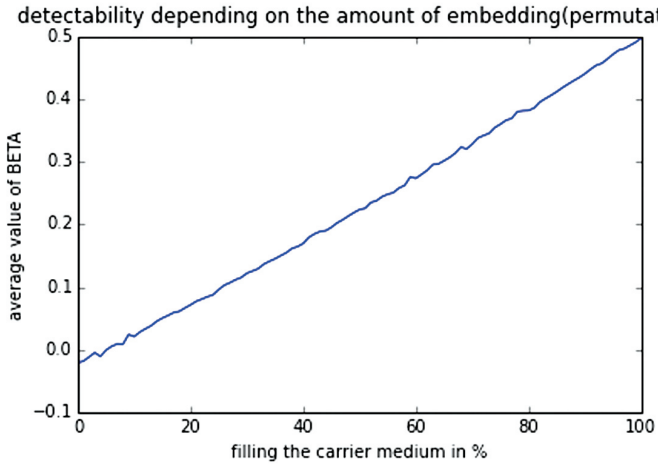

FIGURE 5. Detectability of pseudo-random embedding.

Figure 6 shows the situation when the Hamming codes were enabled in filling the full cover capacity. In contrast with the previous two methods of for steganographic embedding, the values of β are not significant. This fact shows

the average value of β (the red line), which is around zero even in the case of 100 % capacity filling of cover images. Therefore, it is not yet possible to detect such method of embedding by this steganalytical method.

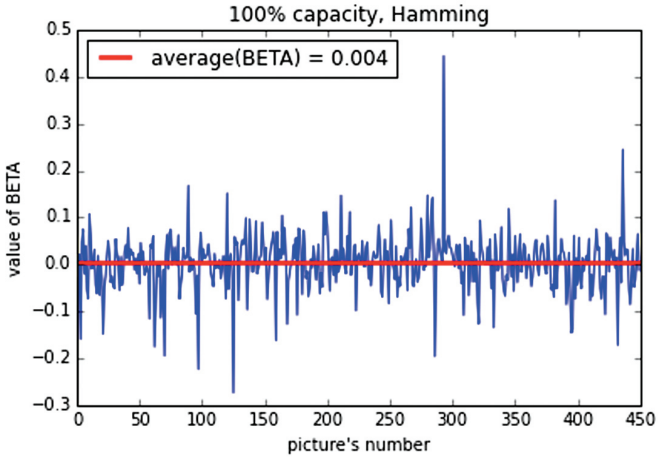

FIGURE 6. Values of β for each image from database, Hamming codes, 100 % capacity filling of cover files.

5. Regular/Singular analysis

Since in the case of the modified WS analysis it was not possible to detect the presence of the secret message in images when Hamming codes were used, a fundamentally different statistical tool was needed. The RS analysis has been thus chosen because it is suitable for pseudo-randomly embedded data.

RS analysis, as is defined in [3], estimates the number of embedding changes by measuring the proportion of *regular* and *singular* non-overlapping n-tuples of spatially adjacent pixels before and after applying three types of flipping functions:

(1) *identity permutation*,

(2) *permutation* $\{-128 \leftrightarrow -127, \ldots, 0 \leftrightarrow 1, \ldots, 126 \leftrightarrow 127\}$,

(3) *shifted permutation* $\{-127 \leftrightarrow -126, \ldots, -1 \leftrightarrow 0, \ldots, 125 \leftrightarrow 126\}$.

To our knowledge, all published research, among them also [11, 12], applies this type of the attack in the spatial domain. In the following paragraph we explain this technique in the frequency domain.

Let us have a cover image with $M \times N$ DCT coefficients, their values are taken from set $P = \{-128, -127, \ldots, 127\}$. We need a discrimination function f, which will capture the frequency correlations. We implement the discrimination function as a population variance. This function measures the smoothness of DCT coefficients group G. It is expected that the value of f will increase after LSB embedding, because the LSB embedding increases the noisiness of the image [11, 12].

We can distinguish three types of DCT coefficients n-tuples: $R-regular$, $S-singular$ and $U-unchanged$, which are defined by the discrimination function f and the flipping function F. The operation of applying the flipping function F to the elements of the vector $G = (x_1, \ldots, x_n)$ will be denoted $F(G)$.The n-tuple G (the group of n DCT coefficients) is:

- *regular* if $f(F(G)) > f(G)$,
- *singular* if $f(F(G)) < f(G)$,
- *unchanged* if $f(F(G)) = f(G)$.

The idea is that for a typical cover image, the relative number of *regular* groups R_M is approximately equal to *regular* groups with inverse flipping mask R_{-M}. This is also true for *singular* S_M and S_{-M}.

The tests were carried out on a single JPEG image with resolution 2000×3008 pixels. The results depended on the selection of the DCT coefficient frequency, group sizes, mask M and the discrimination function f. Our settings were the following:

- the first AC DCT coefficient frequency - coordinates (0, 1),
- group size $n = 5$, then $G = (x_1, x_2, x_3, x_4, x_5)$,
- mask $M = (0, 1, 1, 1, 0)$,
- inverse mask $-M = (0, -1, -1, -1, 0)$,
- discrimination function $f(G) = \sum_{i=1}^{n-1} |x_{i+1} - x_i|$,
- and flipping operation was applied to DCT coefficients with values 0 and 1, too.

Now, we can move on to the test results.

5.1. Results of sequential embedding

In the case that a pseudo-random stream is sequentially embedded into the cover file and 100 percent capacity of the cover media is filled, only about 50 percent of all DCT coefficients are changed. Due to this fact, a buffer inverse of the cover medium was embedded. Therefore, we could change as many DCT coefficients as desired. So, it was possible to simulate even a complete change of all coefficients.

Figure 7 demonstrates the difference between relative numbers of R_M and R_{-M} groups. Ideally, when there is an image without any message, $R_M = R_{-M}$ applies. So, the greater the difference, the more likely it is that the image is a stego image. In practice, unfortunately, each image has a so-called input bias, which is slightly different for every image. It is caused by the input image noise.

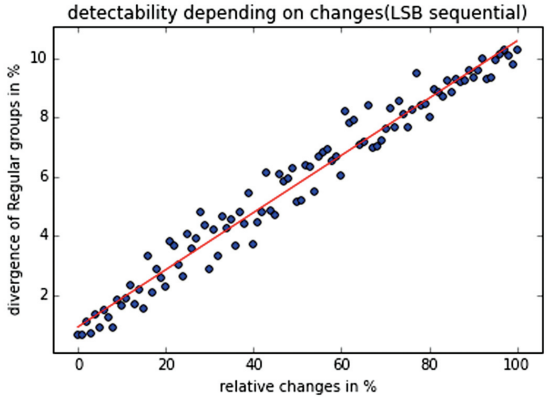

FIGURE 7. The difference between R_M and R_{-M} with the mask $M = (0, 1, 1, 1, 0)$, sequential.

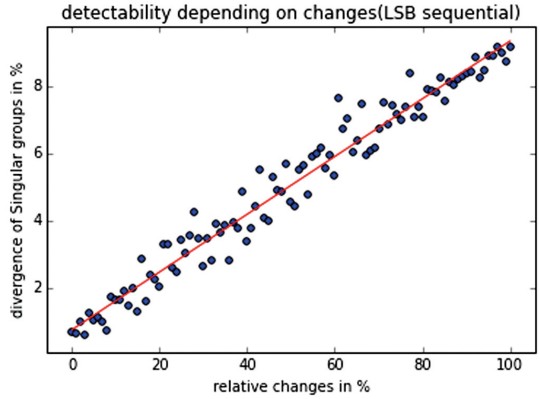

FIGURE 8. The difference between S_M and S_{-M} with the mask $M = (0, 1, 1, 1, 0)$, sequential.

Figure 8 also shows the difference between the relative numbers of S_M and S_{-M} groups. As in the case of *regular* groups, the greater the difference is, the more DCT coefficients were changed. Again, when there is an image without any message, ideally $S_M = S_{-M}$ applies.

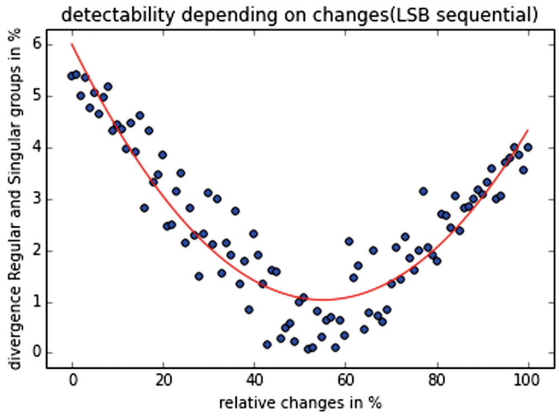

FIGURE 9. The difference between R_M and S_M with the mask $M = (0, 1, 1, 1, 0)$, sequential.

In Figure 9, the difference between relative numbers of R_M and S_M groups can be seen. This difference is almost zero when about 55 % of DCT coefficients are changed. If the experiment was repeated several times, the value of the relative changes would be stabilized at about 50 % due to randomization.

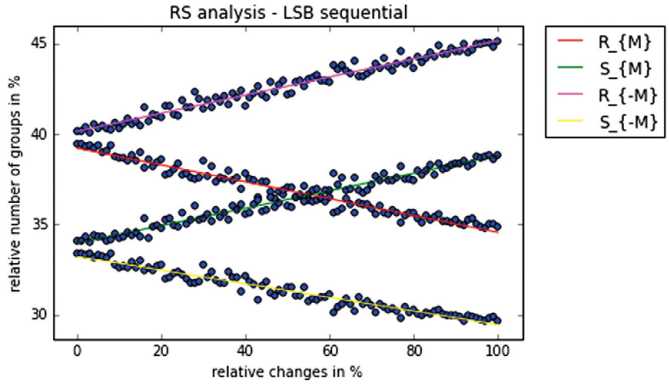

FIGURE 10. The traditional RS diagram with the mask $M = (0, 1, 1, 1, 0)$, sequential.

A typical RS-diagram is shown in Figure 10. The horizontal axis is the percentage of AC DCT coefficients with flipped LSBs. The vertical axis is the relative number of *regular* and *singular* groups. The X-axis with an approximate value of 50 % (the intersection of R_M and S_M) corresponds to embedding of the pseudo-random stream with 100 percent capacity utilization.

5.2. Results of pseudo-random embedding

The results of the pseudo-random embedding are shown in Figures 11, 12, 13 and 14. We omit the description as they are similar to the results of the sequential embedding.

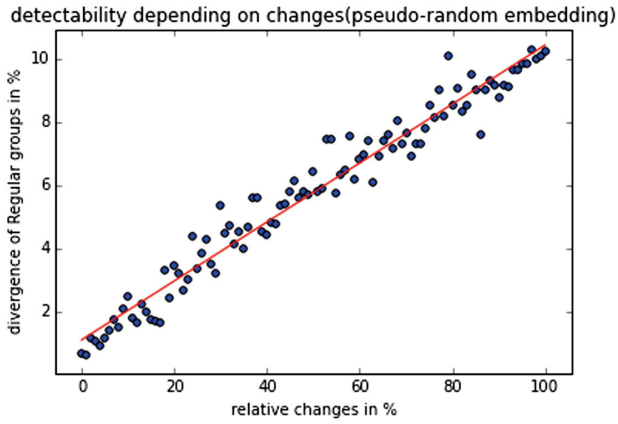

FIGURE 11. The difference between R_M and R_{-M} with the mask $M = (0, 1, 1, 1, 0)$, pseudo-random.

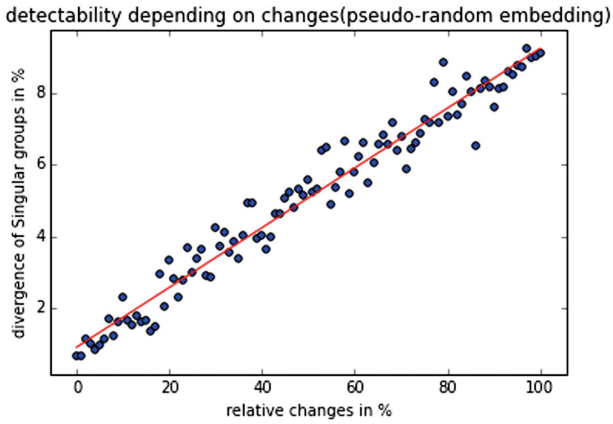

FIGURE 12. The difference between S_M and S_{-M} with the mask $M = (0, 1, 1, 1, 0)$, pseudo-random.

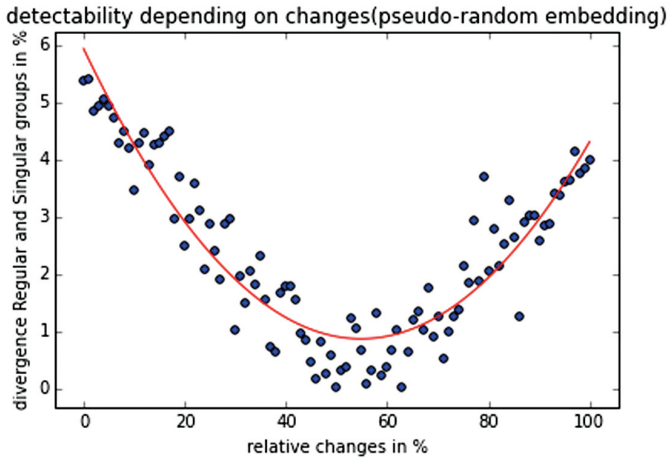

FIGURE 13. The difference between R_M and S_M with the mask $M = (0, 1, 1, 1, 0)$, pseudo-random.

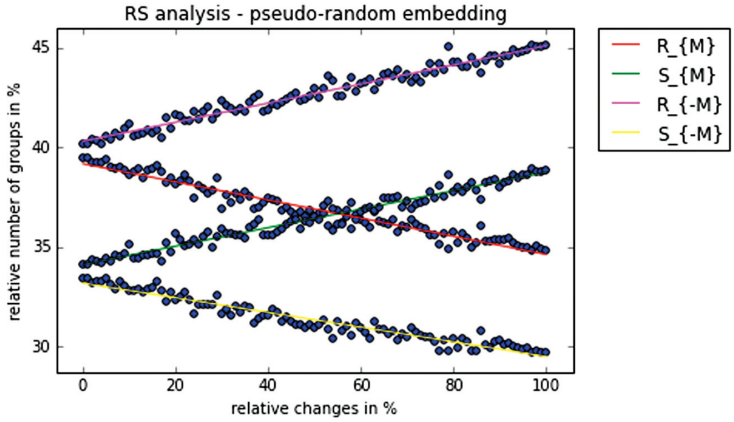

FIGURE 14. The traditional RS diagram with the mask $M = (0, 1, 1, 1, 0)$, pseudo-random.

5.3. Results of Hamming codes

In the context of the Hamming codes it is important to distinguish their type. StegoStorage library allows the use of six different types of these codes for the parameter parity bits $k = 3$, 4, 5, 6, 7 and 8. The default setting of StegoStorage for Hamming codes is $k = 5$. The worst case scenario of these codes in terms of security has been tested, i.e., $k = 3$.

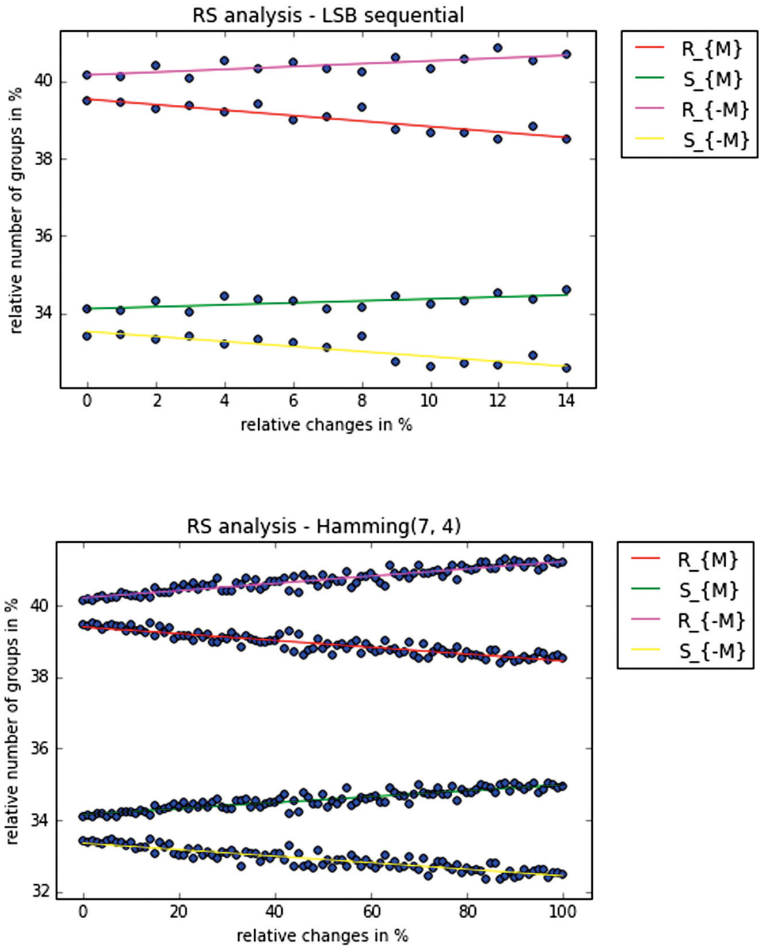

FIGURE 15. Comparison of Hamming codes and sequential embedding.

Figure 15 presents a comparison of a typical RS-diagram when Hamming codes (7, 4) are enabled, that is the parity bits $k = 3$, and a typical zoomed RS--diagram of plain sequential embedding. As it can been seen, the detectability of Hamming codes (7, 4) is equivalent to the detectability of sequential embedding up to 14 % of changed DCT coefficients, which is filling 7 % of the cover capacity with a pseudo-random stream by sequential embedding. Other types of Hamming codes behave similarly, i.e., Hamming(15, 11) is similar to sequential embedding up 6.7 % of changes.

The graph of the $R_M - R_{-M}$ in absolute value is shown in Figure 16 and $S_M - S_{-M}$ in Figure 17.

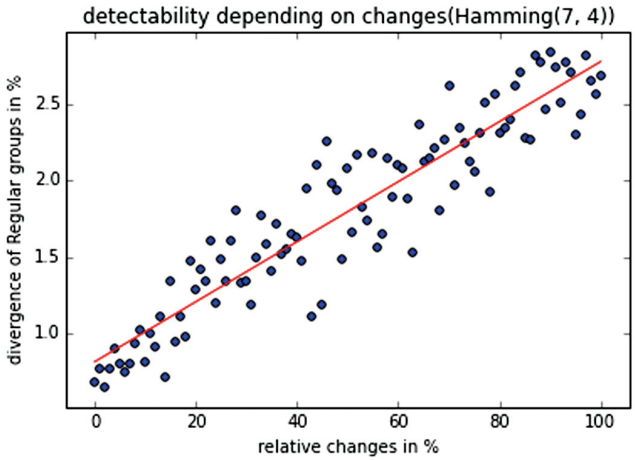

FIGURE 16. The difference between R_M and R_{-M} with the mask $M = (0, 1, 1, 1, 0)$, Hamming code(7, 4).

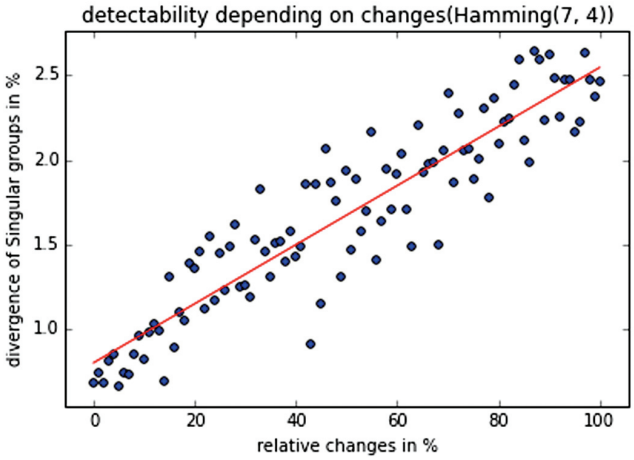

FIGURE 17. The difference between S_M and S_{-M} with the mask $M = (0, 1, 1, 1, 0)$, Hamming code(7, 4).

6. Conclusion

Standard steganalysis techniques along with slightly modified WS and RS analyses have been applied with partial success. The WS analysis was outlined in [13] as the analysis of histogram modifications. We tested this statistical LSB embedding model on all modes of embedding, allowed by the StegoStorage library with all levels of cover file capacity filling. The RS analysis was implemented in the frequency domain because this steganalytic technique should be more suitable for pseudo-random embedding. The aim was to determine the possibility of detecting Hamming codes, which were undetectable when the statistical LSB embedding model was used for steganalysis.

In the case of the statistical LSB embedding model, the results of the tests demonstrate the detectability of sequential embedding from one percent filling of the capacity of the cover files, the detectability of the pseudo-random embedding from approximately ten percent filling of the capacity of the cover files and undetectability when using Hamming codes. Note, that the default setting for Hamming codes (parity bits = 5) was used during the tests. Tests were performed on an image database consisting of 450 JPEG images, which were obtained as original images in the RAW format. All modes of embedding and all percentages of capacity filling, with a step of one percent, were tested.

The results of RS analysis indicate detectability in all modes of embedding, including the Hamming codes. It can be stated that the detection is possible circa from filling the cover file capacity up to 5 % in sequential embedding, which is about 2.5 % of the number of changes in the original media. This threshold of detectable number of changes corresponds to about 15 % of relative number of changes when using Hamming codes with parity bits $k = 3$ (but it is in fact only about 2.5 % of the real number of changes). So theoretically, it could be possible to detect Hamming codes with parity bits $k = 5$ with filling the full capacity of the cover medium, because the maximum number of changes of this Hamming code exceeds the threshold. Therefore, it is advisable to set the default value of parity bits to $k = 6$. The tests were performed on a JPEG image with the resolution of 2000×3008 pixels.

Among others, the next milestone of our research is the concept and the implementation of the attack, which should be able to detect even very few changes in the file. For this purpose, the appropriate method should be the control of the JPEG format.

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Received September 30, 2016

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