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ORIGINAL PAPER

Improved LSB stegananalysis based on analysis of adjacent pixel pairs

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Abstract We propose a simple, reliable method based on probability of transitions and distribution of adjacent pixel pairs for steganalysis on digital images in spatial domain subjected to Least Significant Bit replacement steganography. Our method is sensitive to the statistics of underlying cover image and is a variant of Sample Pair Method. We use the new method to estimate length of hidden message reliably. The novelty of our method is that it detects from the statistics of the underlying image, which is invariant with embedding, whether the results it calculate are reliable or not. To our knowledge, no steganalytic method so far predicts from the properties of the stego image, whether its results are accurate or not.

Keywords LSB replacement · Steganalysis · Adjacent pixel pair

1 Introduction

Steganography hides the secret message in a cover object to obtain a stego object. Digital images, videos, sound files and other computer files that contain perceptually irrelevant or redundant information are used as covers to hide secret messages. The goal of steganalysis is to detect and/or estimate potentially hidden information from observed data with little or no knowledge about the steganographic algorithm or its parameters. The purpose of steganography is to hide the presence of communication, as opposed to cryptography, which aims to make communication unintelligible to those who do not possess the right keys [1]. Least Significant Bit (LSB) replacement, LSB matching, Spread spectrum, etc. are some of the methods used for hiding data. LSB replacement is the most popular and frequently used steganographic method. The popularity of the LSB embedding is due to its simplicity.

There exist many steganalytic techniques in the literature for LSB replacement steganography. The statistical steganalysis proposed by Westfeld and Pfitzmann [2] uses the concept of pairwise dependencies to design a statistical chi-square test to detect the hidden messages. The reported results show that this method reliably detects sequentially embedded messages. Later, the method was generalized to detect randomly scattered messages [3,4].

Fridrich et al. [5] proposes Raw Quick Pair method for detecting LSB embedding in 24-bit color images. The method is based on analyzing close pairs of colors created by LSB embedding. The method works reliably well as long as the number of unique colors in the cover image is less than 30% of the number of pixels. The method has higher detection rate [5] than the method given in [2] but cannot be applied to grayscale images.

Fridrich et al. [6] proposes a more sophisticated technique namely RS steganalysis for the estimation of LSB embedding in color and grayscale images. This method divides the image into disjoint groups of fixed shape. Each group is classified as regular or singular depending on whether the pixel noise within the group is increased or decreased after flipping

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the LSBs of a fixed set of pixels within each group using a mask. The relative numbers of regular and singular groups with embedding form quadratic curves and solving these quadratic equations the amount of embedding is calculated. RS steganalysis is more reliable [6] than chi-square method.

The steganalytic technique proposed by Avcibas et al. [7] looks at 7th and 8th bit planes of an image and calculates several binary similarity measures. The approach is based on the fact that correlation between contiguous bit planes as well as the binary texture characteristics within the bit planes is affected after a message is embedded in an image.

Dumitrescu et al. [8] proposes Sample Pair Method based on the statistics of sample pairs of signal which is highly sensitive to LSB embedding. The technique is based on a finite state machine whose states are selected multisets of sample pairs. On most of the images, this technique precisely measures the length of embedded message, even when the hidden message is very short relative to the size of image. This method is more accurate than method given in [6].

Improvements of this method are proposed in [9], where marginal and joint probabilistic distributions of the image are analyzed using texture co-occurrence matrix. However, for fixing a threshold for reducing the estimation error, the cover image is required. A variant of technique given in [8] is proposed by Lu et al. [10], where the problem is treated as one of least square estimation. It has been shown that the technique improves estimation accuracy on a set of test images.

Dumitrescu et al. [11] proposes another method that utilizes higher order statistics for deriving detection equations and estimates hidden message length by measuring distinguishing statistics. The method is reported to be robust and effective on both color and grayscale natural images.

Bohme [12] shows that RS steganalysis and Sample pair method are prone to error, and the error distribution curves of these estimators follow cauchy distribution with fat tails owing to the extreme ouliers yielding unreliable results. Ker [13] shows that least quare method has heavy tails and a slight negative bias. Thus, these methods are unreliable on some images and by far we do not have a handle as to which image gives unreliable results.

In this paper, we present a new method for detecting and estimating the length of hidden messages along with an indication on the reliability of estimation. From certain properties of images which are invariant with embedding, it detects whether estimation is reliable or not. It makes the length estimation by considering both spacial adjacency and chromatic adjacency simultaneously. The method we propose is based on the assumption that in natural images, mostly neighboring pixels have same color values and when LSB embedding is done randomly, the adjacent pixel pair with same value become a pair that can be resulted due to embedding. We estimate the message length from the count of these two type of pairs.

The rest of this paper is organized as follows: Sect. 2 details the notations we use in the paper. Section 3 describes the new method for steganalysis. Section 4 shows the experimental results we obtained. Section 5 is the conclusion and future work.

2 Notations

We consider the *RGB* color representation of pixels in an image in *uncompressed raw format* and we treat R, G, B planes separately.

P: Multiset of sample pairs (u, v) drawn from digital image

X_n : Sub multi set of P that consists of sample pairs drawn from cover signal and whose values differ by n and in which even value is larger

Y_n : Sub multi set of P that consists of sample pairs drawn from cover signal and whose values differ by n and in which odd value is larger

C_m : Sub multi set of P that consists of sample pairs drawn from cover signal and whose values differ by m in the first $(b-1)$ bits (i.e., by right shifting one bit and then measuring the difference of m)

D_0 : Sub multi set of P that consists of sample pairs drawn from cover signal and whose values differ by 0

X'_n, Y'_n, C'_m, D'_0 : The respective sub multi sets of P after LSB replacement

p : Estimated length as percentage of number of pixels in the image

b : Number of bits to represent a sample value

$\lambda = \frac{100|C_0|}{\sum_{m=0}^{2^{b-1}-1} |C_m|}$

$\tau = 0.20 \times \mid P \mid$

3 Steganalysis technique based on analysis of adjacent pixel pairs

In an image, neighboring pixels mostly have same color values. With embedding, color values of neighboring pixels change. However, embedding cannot change pixel values arbitrarily. Based on the above observations, we propose

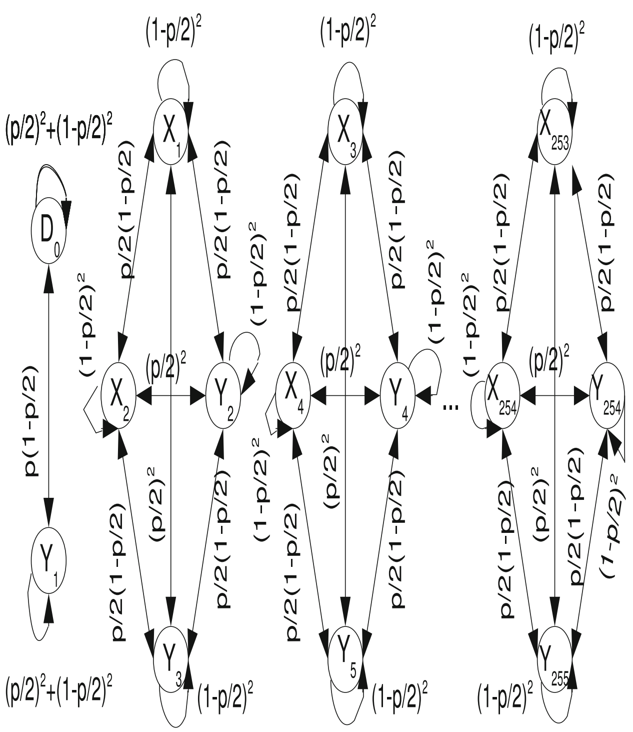

Fig. 1 Probable transitions due to embedding on adjacent pixel pairs of an image: *arrow labels* indicate probability of transitions

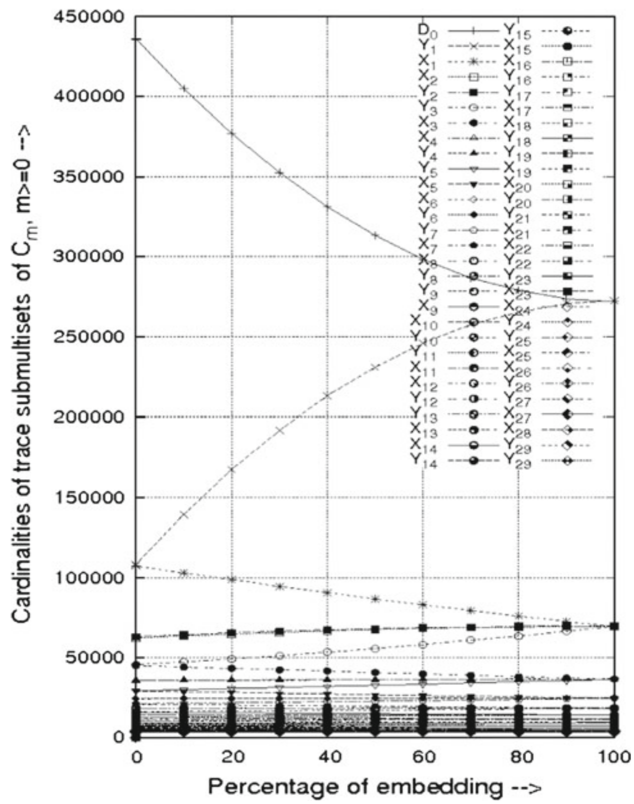

Fig. 2 Typical variation in cardinalities of blocks of Cms with embedding

a new method for steganalysis based on analysis of transitions in adjacent pixel pairs. We call the set of horizontally or vertically adjacent pixel pairs P.

We analyze the transitions in P due to embedding as detailed in [8]. Transitions analyzed are shown in the transition diagram in Fig. 1. Based on the transitions due to embedding P can be partitioned into $C_0, C_1, C_2, \ldots C_{2^{b-1}-1}$. Each $C_m, m \geq 1$ is further partitioned to X_{2m-1}, X_{2m}, Y_{2m}, and Y_{2m+1} and C_0 to D_0, and Y_1. The transitions due to embedding are confined between blocks of each C_m and cardinalities of these blocks change with embedding.

Generally $| X_{2m-1} | \geq | X_{2m} | \approx | Y_{2m} | \geq | Y_{2m+1} |$. Hence, due to embedding, $| X_{2m-1} |$ decreases and $| Y_{2m+1} |$ increases. $| X_{2m} |$ and $| Y_{2m} |$ increase/decrease depending on their initial value. At 100% embedding, all these cardinalities become equal. The decrease/increase in $| X_{2m-1} |$ / $| Y_{2m+1} |$ are quadratic when difference between $| X_{2m-1} |$ and $| Y_{2m+1} |$ is large. The decrease/increase in $| X_{2m} |$ and $| Y_{2m} |$ is linear. Typical change in cardinalities of the blocks of C_ms is as shown in Fig. 2.

In a cover image $| X_i | \approx | Y_i |, 0 \leq i \leq 2^b - 1$ [8]. Generally, in an image, $2 | C_0 | \geq | C_1 | \geq \cdots \geq | C_{2^{b-1}-1}$ [8]. In general, when $| C_0 |$ is large, variation of $| C_m |$ with m is shown in Fig. 3. Since the transitions due to embedding are contained within each C_m, cardinalities of all C_ms are invariants with embedding. It is clear from

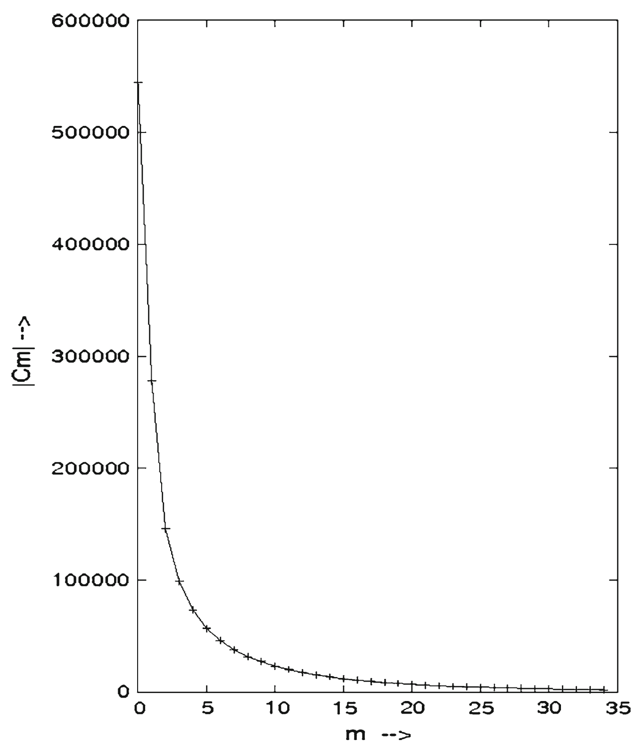

Fig. 3 Typical variation in $| Cm |$ with m

Fig. 2, when $|C_m|$ is small, curves of $|X_{2m-1}|$ and $|Y_{2m+1}|$ with respect to embedding are almost horizontal lines.

Hence, when $|C_m|$ is small, $|X_{2m-1}| \approx |X'_{2m-1}|$
We know $|Y_{2m-1}| \approx |X_{2m-1}|$
Thus, we have, $|Y_{2m-1}| \approx |X'_{2m-1}|$
Since $|C_{m-1}|$ is an invariant with embedding,

$$|X_{2m-3}| \approx (|X'_{2m-3}| + |X'_{2m-2}| + |Y'_{2m-2}| + |Y'_{2m-1}|) - (|X'_{2m-2}| + |Y'_{2m-2}| + |Y_{2m-1}|)$$

$$|Y_{2m-3}| \approx |X_{2m-3}|$$

$$|X_1| \approx (|X'_1| + |X'_2| + |Y'_2| + |Y'_3|) - (|X'_2| + |Y'_2| + |Y_3|)$$

$$|Y_1| \approx |X_1|$$

$$|D_0| \approx (|D'_0| + Y'_1|) - |Y_1|$$

We know

$$|D'_0| \approx |D_0|(1 - p(1 - p/2)) + |Y_1|(p(1 - p/2)) \quad (1)$$

Now solving the above quadratic equation, p, the amount of hidden data, can be estimated. The algorithm for hidden length estimation is given in Algorithm (1). The value of $|X'_{2i-1}|$ is empirically chosen as less than or equal to $0.008\times |P|$ so that variation of X'_{2i-1} is almost 0 with embedding.

Algorithm 1 Hidden length estimation algorithm

```
Evaluate λ.
if λ below the threshold τ then
  conclude results are unreliable.
else
  Find biggest |X'_{2i-1}| such that |X'_{2i-1}| ≤ 0.008× |P|.
  Fix estimate of |Y_{2i-1}| as |X'_{2i-1}|
  Back substitute and find estimates of |Y_1| and |D_0|
  Solve the quadratic equation (1) for p
end if
```

We make the following assumptions to make the estimation accurate.

- the parity difference is small in C_ms under consideration
- the slope of the curves $|X_{2m}|$ and $|Y_{2m}|$ are very small
- the distribution of $|C_m|$s follows the condition: $2|C_0| \geq |C_1| \geq |C_2| \geq \cdots |C_{2^{b-1}-1}|$

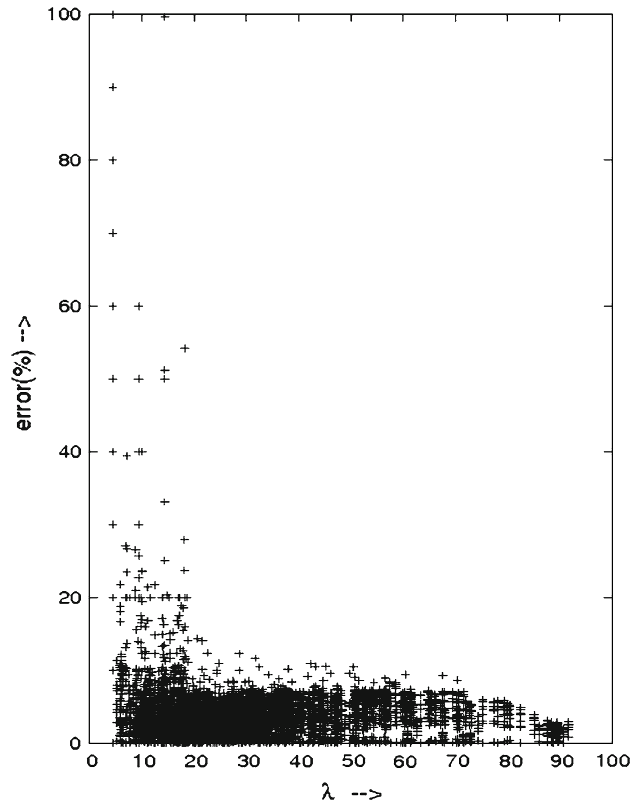

Fig. 4 Estimation error against different values of λ

The assumptions regarding the parity difference and distribution of C_ms are the same as in [8], and the assumption regarding the slope of the curves results from the other two assumptions. In fact, the our assumptions are more relaxed as they are to be satisfied only for C_ms, which are considered for estimation. Violations of above assumptions can cause mild estimation errors.

We estimate p using $|C_0|$. For estimation, the law of large numbers is used. Hence, the estimation errors are less if $|C_0|$ is large. When $|C_0|$ is very small, the estimated results are highly inaccurate. The relationship between the estimation error and value of λ is depicted in Fig. 4.

Since λ is an invariant with embedding, depending on its value, from the given image, we can predict whether the results are accurate or not. To our knowledge, *no steganalysis method so far has an inbuilt mechanism of this kind.*

4 Experimental results

We performed tests on a database of one thousand 24-bit color images. The images were taken by Nikon Coolpix 8400, which were originally stored as high-quality JPEG images. For our test purposes, we converted them to.pnm format using linux utility jpegtopnm and cropped to 800 × 600 size.

Table 1 Estimation accuracy shown our method and SPM

Level of embedding ($e\%$)	Average estimation error			Maximum estimation error		
	Our method	SPM	LSM	Our method	SPM	LSM
0	0.0148	0.0340	0.0265	0.0727	0.90542	0.9348
10	0.0292	0.0342	0.0242	0.0788	0.8173	0.7342
20	0.0390	0.0304	0.0214	0.0832	0.7282	0.5354
30	0.0436	0.0294	0.0189	0.0809	0.6283	0.3828
40	0.0447	0.0309	0.0161	0.0783	0.6001	0.1734
50	0.0430	0.0324	0.0141	0.0726	0.5002	0.4894

4.1 Estimation of length of hidden message

We embedded messages of length 10, 20, $\cdots$, 100% onto the set of 1,000 cover images and estimated the message length. The average and maximum estimation error at various levels of embedding shown are given in Table 1. For tabulation of the results of our method, the images with λ below τ are not included. The strength of the proposed method is that the maximum estimation error for any amount of embedding does not exceed 10% thus reducing length of the tails of error distribution considerably. This in turn increases the reliability of steganalysis. The average estimation error is comparable with SPM. The results are more reliable when embedding ratio is small.

4.2 Comparison with other steganalysis methods

There are many reliable methods such as RS steganalysis [6], Sample Pair Analysis [8], and Improved Sample Pair Method [10] for estimation of LSB replacement steganography. Though they give highly accurate results on most of the images, they give highly inaccurate results on some images. There is no clue available to the psychanalyst as to where they work reliably and where they do not. This is the case with all steganalysis methods in the literature. For error analysis, the corresponding cover images are required.

The method we proposed indicates the steganalysis results are unreliable if λ is very small. No steganalysis method so far gives such an error indication. The proposed method takes $\mid C_0 \mid, \mid C_1 \mid, \cdot\cdot \mid C_i \mid$ where $\mid X_{2i-1} \mid$ is not very small say $\mid X_{2i-1} \mid \geq 0.008 \mid P \mid$. The value of i depends on the statistical distribution of C_is in the image. The average value of i on the image set tested is 4 and its value varied from 2 to 8. In RS steganalysis, all C_is, $0 \leq i \leq 127$, and in the case of SPM, C_is, $0 \leq i \leq 30$ are taken for estimation. In the case of LSM, only C_is, $0 \leq i \leq 5$ are considered.

The advantage of our method is that from stego image we can predict whether the method can do a reliable estimation or not. Other methods can do error analysis only if the cover image is known. However, if LSB embedding is done cleverly in active regions in a cover image, our method may or may not give reliability indication correctly. If cover image has larger active regions such that $\mid C_0 \mid$ is less than threshold τ, our method will indicate the results as unreliable. If the image has very small areas of active regions such that $\mid C_0 \mid$ is greater than threshold τ and embedding done in active regions alone, our method incorrectly indicates the results as reliable.

5 Conclusions and future work

In this paper, we discussed a new method for reliably estimating length of hidden message in digital images in uncompressed raw format that have been subjected to LSB replacement steganography taking into account both spatial adjacency and chromatic adjacency simultaneously. Our experimental results show that average estimation error is comparable to the most robust techniques in the literature for message length estimation especially for small embedding ratios. The novelty of the method is that from certain properties, which are invariant with embedding, we are able to predict whether the estimated results are reliable or not. In order to compare the performance of various steganalysis methods, either the image set has to be standardized or we should be able to specify an image set in terms the values of certain parameters. Our future work is directed toward this.

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