Security analysis of a self-embedding fragile image watermark scheme

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Abstract

Recently, a self-embedding fragile watermark scheme based on reference-bits interleaving and adaptive selection of embedding mode is proposed. Reference bits are derived from the scrambled MSB bits of a cover image, and then are combined with authentication bits to form the watermark bits for LSB embedding. We find this scheme has a feature of block independence of embedding watermark such that it is vulnerable to a collage attack. In addition, because the generation of authentication bits via hash function operations is not related to secret keys, we can apply a multiple stego-image attack on this scheme and the cost of acquiring all the permutation relations (i.e., equivalent permutation keys) of \( l \cdot b^2 \) watermark bits of all blocks is about \( (l \cdot b^2)! \) for the embedding mode \((m, l)\), where \( m \) MSB layers of a cover image are used for generating reference bits and \( l \) LSB layers for embedding watermark, and \( b \times b \) is the size of image block. The simulation results and the statistical results demonstrate our analysis is effective.

Keywords: Fragile watermark, Collage attack, Multiple stego-image attack, Image authentication, Security analysis

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1. Introduction

With the development in science and technology, digital images are easily processed and widely used [1, 13]. To ensure the integrity of digital images, image authentication techniques based on fragile watermark have been studied [9, 14]. Haouzia et al. [6] discussed the general requirements of an authentication system, such as its security, the sensitivity of watermark, the accuracy of tampering localization. We consider security the most important one. Any authentication system must protect the authentication data against any falsification attempts.

There are multiple image authentication schemes based on fragile watermark proposed by scholars [5, 10, 17, 22, 24, 25]. However, some of them only pursue the accuracy of tampering detection and the quality of recovered image. There still exist the security problems, which are vulnerable to counterfeiting attack. Yeung and Mintzer [21] proposed a fragile watermark scheme where fragile watermark is generated via a lookup table. The table map the value of pixels to 0 or 1 bit controlled by the secret keys. However, there is a security risk that the mapping relations are not related to the image content. Holliman and Memon proposed a vector quantization (VQ) attack to break this scheme [7]. Chang et al. [3] proposed a watermark algorithm based on hash functions. The authentication bits are generated via a cryptographic hash function, and then inserted into the lowest significant bit (LSB) of the

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center pixel in a corresponding block. However, Phan [15] proposed an effective method to break this scheme. Lin et al. [9] proposed a hierarchical watermark method, where the feature of each block of the image is embedded into another block. This scheme uses both reference bits and authentication bits to detect tampered area. However, Chang et al. [2] proposed a four-scanning attack to find the block-mapping sequence, and furthermore to counterfeit authenticated images successfully. A scheme with high data hiding capability and fidelity preservation was proposed by Lin et al. [11]. However Li et al. [12] proposed an analysis method to counterfeit authenticated images. Rawat and Raman [18] proposed a scheme based on chaotic map and Teng et al. [20] found this scheme cannot resist a content-only attack. Without knowing the secret key, an attacker first stores the LSBs of the watermarked image. Then he or she alters the pixels and replace their LSBs stored before. The main reason is that the authentication data is irrelevant to the cover image.

Qin et al. [16] proposed a self-embedding fragile watermark scheme based on reference-data interleaving and adaptive selection of embedding mode. The choice of embedding mode is related with watermarked image quality, estimated tampering rate, and recovered image quality. The authors claimed that the proposed scheme can achieve good visual quality of recovered images under different tampering rates. To improve the sensitivity of authentication data in the scheme, hash function operations are utilized to generate authentication data. Though this scheme is flexible and has good ability in recovering tampered image, we find it vulnerable to a collage attack. The scheme has a fatal defect that the authentication bits of each block only embed into the corresponding block. This feature is called block independence. This weakness makes this scheme not resist the collage attack. Besides, the generation of authentication bits via hash function operations is not controlled by secret keys and the authentication bits embed in the fixed positions that are not related with the cover image. Therefore, based on the two characteristic above, if an attacker obtains embedding positions of watermark, he or she can forge any authenticated images.

The remaining parts of the paper are organized as follows. Section 2 describes the conditions of security analysis of fragile watermark. In Section 3, we introduce Qin et al.’s scheme briefly. In Section 4 we analyze the security of Qin et al.’s scheme by using the collage attack and multiple stego-image attack. Conclusion of this paper is given in Section 5.

2. Conditions of security analysis of fragile watermark

Besides VQ attack [7] and collage attack [5] etc, there also exist general tampering attacks, such as copy-paste attacks, deletion attacks, text insertion attacks etc [19]. Considering analysis conditions, the attack methods can be classified into the following types [4].

**Stego-image attacks.** The attacker has only one authenticated image. The aim is to modify the image such that it is undetected or obtain some secret information of the scheme.

**Multiple stego-image attacks.** The attacker has multiple authenticated images. The aim is to modify or forge one image such that it is undetected, or to obtain some secret information of the scheme.

**Verification device attacks.** The attacker has access to the verification device, i.e., the attacker can verify the authenticity of any image. In this condition, the attacker is interested in making undetected changes or obtaining some secret information of the scheme.
Cover-image attacks. The attacker has multiple pairs of original-authenticated images. Again, the attacker is interested in making undetected changes or obtaining some secret information of the scheme.

Chosen cover-image attacks. The attacker has access to the authentication device and can submit her or his images for authentication. The aim is to obtain some information about the secret authentication key.

3. Brief description of Qin et al.’s scheme

First, we describe Qin et al.’s scheme briefly. This scheme is a self-embedding image authentication scheme. In the original scheme, $m$ MSB layers of a cover image are used for the generation of reference bits, and the reference bits and the $m'$ MSB layers are further used for the generation of authentication bits ($m'$ is the minimum of two values $m$ and $8 - l$, where $l$ LSB layers are used for embedding). The authentication and reference bits are embedded in $l$ LSB layers of the cover image. There exist two working modes: overlapping-free embedding ($m + l \leq 8$) and overlapping embedding ($m + l > 8$). The choices of $m$ and $l$ are related to many factors, such as watermarked image quality, estimated tampering rate, and recovered image quality.

3.1. Watermark embedding

In this scheme, the embedding and detecting of watermark are based on image block. For a block size of $b \times b$, $l \cdot b^2$ bits are embedded in $l$ LSB layers of each block, containing $L_a$ authentication bits and $l \cdot b^2 - L_a$ reference bits. The generation of reference and authentication bits, and the watermark embedding procedure are shown below.

**Step 1.** Image grouping. Divide a cover image of size $N_1 \times N_2$ into $N/b^2$ blocks, where $N = N_1 \times N_2$. For simplicity, $N_1$ and $N_2$ are assumed to be the multiples of $b$.

**Step 2.** Permutation. Collect $m$ MSB layers of the cover image, and permute the $m \cdot N$ bits with a secret key to form a set $C$.

**Step 3.** Generate reference bits. Divide $C$ into $S$ subsets noted as $C_1$, $C_2$, ... , $C_S$. Each subset contains $u$ bits. Each subset is transformed by the following expression

$$
\begin{bmatrix}
  r_{j,1} \\
  r_{j,2} \\
  \vdots \\
  r_{j,u}
\end{bmatrix} = H_j \cdot \begin{bmatrix}
  c_{j,1} \\
  c_{j,2} \\
  \vdots \\
  c_{j,u}
\end{bmatrix}
$$

where $H_j$ is a pseudo-random binary matrix of size $v \times u$ produced from a secret key. After the transformation above, there are $v \cdot S = v \cdot m \cdot N/u$ bits named the reference bits, furthermore, the value of $v$ should satisfy the expression

$$
v \cdot S = v \cdot m \cdot N/u = l \cdot N - L_a \cdot N/b^2
$$

**Step 4.** Generate authentication bits. For each block, feed $m' \cdot b^2$ bits of the $m'$ MSB layers and corresponding $l \cdot b^2 - L_a$ reference bits into a hash function and generate $L_a$ authentication bits.

**Step 5.** Embed watermark. Permute the $l \cdot b^2$ watermark bits of each block with a secret key (containing $L_a$ authentication bits and $l \cdot b^2 - L_a$ reference bits) and use them to replace the $l$ LSB layers of each block.
3.2. Tampering detection

In this scheme, a receiver not only verify the integrity of suspicious watermarked image $I_w^*$, but also has ability to recover tampering area. Here we only describe the tampering detection procedure.

For each $b \times b$ block of $I_w^*$, first extract the $l \cdot b^2$ bits of its $l$ LSB layers consisting of $L_a$ authentication bits and $l \cdot b^2 - L_a$ reference bits. There are two modes of tampering detection:

1) Overlapping-free embedding: Feed the $m \cdot b^2$ MSB bits of each block and the $l \cdot b^2 - L_a$ reference bits into a hash function and output $L_a$ authentication bits. If the recalculated $L_a$ bits differ from the extracted $L_a$, this block is judged as a tampered block. Otherwise, it is marked as an intact block.

2) Overlapping embedding: Feed the $(8 - l) \cdot b^2$ MSB bits of each block and the $l \cdot b^2 - L_a$ reference bits into a hash function and output $L_a$ authentication bits. Similar to overlapping-free embedding mode, if the recalculated $L_a$ bits differ from the extracted $L_a$, this block is judged as a tampered block. Otherwise, it is an intact one.

4. Security analysis of Qin et al.’s scheme and simulation results

4.1. A collage attack

One defect of this scheme is that the authentication bits generated by one block are embedded into the same block. This means that each block verification with unchanged secret keys is independent. This defect leads to be vulnerable to attack of a collage of images. The collage attack is effective for overlapping-free embedding mode and overlapping embedding mode. The details of the collage attack are shown as follows.

**Attack aim:** The aim of this attack is to forge a new image produced from authenticated images.

**Attack Conditions:** A forger has multiple authenticated images with the same embedding mode and the unchanged secret key, although she or he doesn’t know the key.

**Step 1.** For an authenticated image $A$, a forger first marks the block according to the block size $b \times b$ and selects an area to be tampered. And this area must be an integral multiple of a block, named $y$.

**Step 2.** Given another authenticated image $B$, which has the same authentication mode as the image $A$. Same as $A$, the authenticated image $B$ is blocked through $b \times b$ and the area $y$ of $B$ is selected.

**Step 3.** Replace the area $y$ of $A$ with the area $y$ of $B$, and finish a forged image $A'$.

**Step 4.** Verification operation. Because the tampered area $y$ is an integral multiple of the size of a block and the verification procedure is block independent, the tampered image $A'$, as an intact image, can pass tampering detection and cannot be found that it has been tampered.

To verify our analysis above, we give an example using the collage attack. The simulation results are shown in Fig.1. Figures 1(a-d) are four authenticated images with the same embedding mode $(6,2)$, i.e., $m = 6, l = 2$. The size of these images is $512 \times 512$ and the size of a block is $b = 1 \times 1$. We take a quarter of each image and construct a collage image shown in Fig.1(e). The collage image successfully passes tampering detection and the result of tampering detection is presented in Fig.1(f). The simulation results show that Qin et al.’s scheme cannot resist the collage attack.
4.2. Multiple stego-image attack

The aim of this attack is to obtain the equivalent permutation relation of the $l \cdot b^2$ watermark bits in each block. Once the attacker acquires these permutation relations of image blocks, she or he can forge authenticated images such that they pass tampering detection. In embedding procedure, there are two weakness that are able to cause security problems shown as follows.

**Weakness 1:** For each $b \times b$ block, $m' \cdot b^2$ bits of its $m'$ MSB layers and its corresponding $l \cdot b^2 - L_a$ reference bits are fed into a hash function to generate $L_a$ authentication bits. In this operation, we find that there is no secret key participating. In other words, anyone can implement this operation.

**Weakness 2:** After generating authentication bits for each block, we need permute the $l \cdot b^2 - L_a$ reference bits and $L_a$ authentication bits through a secret key and then embed $l \cdot b^2$ bits in the $l$ LSB layers of each block. Assume that the permutation key is unchanged for each block. For $l \cdot b^2$ watermark bits, the maximal permutation numbers are $(l \cdot b^2)!$. Therefore, if an attacker obtains the permutation relation of watermark bits for each block, she or he is able to forge any authenticated images.

**Attack aim:** The aim of this attack is to obtain the equivalent permutation key (i.e., permutation relation) of the $l \cdot b^2$ watermark bits in each block.

**Attack Conditions:** An attacker has two authenticated images with mode $(m, l)$.

**Step 1.** Given an authenticated image with mode $(m, l)$, we first analyze its 1st block. We extract the $l \cdot b^2$ watermark bits and separates them into two parts, $l \cdot b^2 - L_a^* \text{ reference bits and } L_a^* \text{ authentication bits.}$ The $l \cdot b^2$ bits have different permutation relations and the permutation number is expressed by the form $(l \cdot b^2)!$  \( (3) \)

**Step 2.** Choose one of all permutation relations and calculate its authentication bits $L_a^{**}$. Feed $m' \cdot b^2$ bits of its $m'$ MSB layers and the $l \cdot b^2 - L_a^*$ reference bits into a hash function and generate authentication bits $L_a^{**}$.

**Step 3.** Compare $L_a^*$ and $L_a^{**}$. If $L_a^{**} \neq L_a^*$, the assumed permutation is wrong, otherwise it may be right. Furthermore, we take another authenticated image to verify this permutation relation.

**Step 4.** Parallel processing all blocks. We execute the parallel process of blocks of the authenticated image from steps 2 to 3. To acquire the correct permutation of $l \cdot b^2$ watermark bits, we need test about $(l \cdot b^2)!$ times, which is not related to the image size. Table 1 lists the test number of analysis for different block sizes and embedding modes. From Table 1 we can observe that the security of Qin et al.’s scheme decreases with decrease of block size of the image and embedding layer of the watermark.
Table 1: The test number of multiple stego-image attack for different block sizes and embedding modes.

| Block size | Mode     | Test number |
|------------|----------|-------------|
| 1 × 1      | (6,2)    | 2           |
| 1 × 1      | (6,3)    | 6 ≈ 2^2.6   |
| 2 × 2      | (6,2)    | 40320 ≈ 2^{15.3} |
| 2 × 2      | (6,3)    | 4.7900 × 10^8 ≈ 2^{28.8} |
| 4 × 4      | (6,2)    | 2.6313 × 10^{35} ≈ 2^{117.6} |
| 4 × 4      | (6,3)    | 1.2414 × 10^{61} ≈ 2^{202.9} |

5. Conclusion

This paper points out the defects that exist in Qin et al.’s scheme. Based on the block independence of watermark embedding, we can forge a new authenticated image from authenticated images via the collage attack. The simulation results verify our theoretical analysis. Furthermore, we analyze the security of Qin et al.’s scheme by using multiple stego-image attack. Because the generation of authentication bits isn’t related to a secret key, once an attacker acquires the permutation relations of \( l \cdot b^2 \) watermark bits of all blocks, she or he can forge any authenticated images. The cost of acquiring all the permutation relations is about \( (l \cdot b^2)! \). Enhancing the security of fragile watermarking algorithms has been a challenge and we hope our analysis method will promote the research of fragile watermarking to some extent.

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