

Postprint of Halftone Self-Hiding Algorithm Based on Dot Diffusion and Error Diffusion

Authors: Ding Haiyang

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Abstract

A secret image is hidden within a halftone image based on dot diffusion or error diffusion, thereby implementing halftone self-hiding algorithms based on dot diffusion and error diffusion; a dot diffusion-based grayscale halftone self-hiding algorithm is realized based on the dot diffusion-based bidirectional conjugate information hiding algorithm, which is then extended to error diffusion-based grayscale halftone images, leading to the proposal of an error diffusion-based grayscale halftone self-hiding algorithm; building upon the latest new conjugate data hiding algorithm for both dot diffusion and error diffusion, dot diffusion and error diffusion-based color halftone self-hiding algorithms are proposed. Four categories of self-hiding algorithms are subjected to experimental validation, and the performance of different halftone self-hiding algorithms is compared. The results demonstrate that under identical parameters, the error diffusion-based color halftone self-hiding algorithm exhibits the best performance.

Full Text

Preamble

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Halftone Self-Hiding Algorithms in Dot Diffused and Error Diffused Halftone Images

Ding Haiyang^{1, 2}

(1. College of Information Engineering, Beijing Institute of Graphic Communication, Beijing 102600, China;

2. Information Security Center, Beijing University of Posts & Telecommunications, Beijing 100876, China)

Abstract: This paper proposes halftone self-hiding algorithms that enable a secret image to be concealed within either a dot-diffused or error-diffused halftone image. Building upon the data hiding algorithm by dual conjugate dot diffusion, we implement a dot-diffused grayscale halftone self-hiding algorithm and extend this approach to error-diffused halftone images, thereby proposing an error-diffused grayscale halftone self-hiding algorithm. Based on the latest color halftone visual cryptography algorithms—new color conjugate error diffusion and new color conjugate dot diffusion—we further propose color halftone self-hiding algorithms for both dot-diffused and error-diffused halftone images. Experimental validation of the four self-hiding algorithms is conducted, with performance comparisons across different halftone self-hiding approaches. Results demonstrate that under identical parameters, the color halftone self-hiding algorithm based on error diffusion achieves the best performance.

Keywords: halftone; dot diffusion; error diffusion; self-hiding

0 Introduction

Halftone images represent a unique image carrier that expresses continuous-tone images using only two color values (black and white). Conventional image hiding algorithms cannot be directly applied to halftone images, making information hiding in halftones a novel research challenge in the field of image steganography. Halftoning methods (also known as screening methods) for converting continuous-tone images into halftone representations primarily include ordered dithering [2], error diffusion [3-5], dot diffusion [6-7], and direct binary search [8-9]. Correspondingly, different halftone information hiding algorithms have been developed for each method.

One approach modifies local region characteristics of a halftone image to embed watermark information; these are called dot watermarking algorithms [10-13], which are only applicable to ordered dithering halftone images. However, ordered dithering produces relatively low-quality halftone images. To improve image quality, error diffusion and dot diffusion methods are now more commonly employed. For these two halftone types, the primary information hiding approach is halftone visual cryptography (HVC), which conceals a binary secret image across multiple halftone images by modifying the relative relationships of corresponding pixels.

In HVC, the most widely used scheme is (2,2) HVC, which hides a secret image in two halftone images and requires both images for secret extraction. Fu and Au [14] proposed Data Hiding by Conjugate Error Diffusion (DHCED), which embeds a secret image in two error-diffused halftone images. The first halftone image is generated using standard halftoning, while the halftoning process of the second image is modified using the conjugate concept to ensure that corresponding pixels in the two images are conjugates when the original image data is black (0). While this approach successfully employs the conjugate concept

for secret image hiding, it only allows modification of the second image' s data during the embedding process.

Guo et al. [15] proposed two algorithms: Data Hiding by Conjugate Dot Diffusion (DHCDD) and Data Hiding by Dual Conjugate Dot Diffusion (DHDCDD), both of which hide a secret image in two dot-diffused halftone images. DHCDD extends DHCED [14] from error diffusion to dot diffusion halftone images, while DHDCDD enables modification of data in both halftone images during the hiding process to achieve conjugation, a concept termed dual conjugation. The advantage of DHDCDD lies in its dual conjugation concept, though its limitation is applicability only to grayscale halftone images.

Ding [16] implemented and extended various grayscale halftone information hiding algorithms, concluding from experimental results that dual-conjugate-based information hiding algorithms outperform single-conjugate approaches. For grayscale halftone images, DHDCDD [15] and DHCED [16] demonstrate the best performance. Fu and Au [17] proposed a Color Conjugate Error Diffusion (CCED) algorithm for color halftone images, which hides a secret image in two color error-diffused halftone images by selecting one color component with minimal interference for conjugate-based information hiding. While this method' s advantage is selecting the least disruptive color component, its extraction performance suffers when the secret pattern is hidden across two different halftone images.

Guo et al. [18] extended DHDCDD [15] from grayscale to color halftone images, proposing Dual Conjugate Color Dot Diffusion (DCCDD) for hiding secret images in color dot-diffused halftone images. This algorithm offers three advantages: it can hide secret patterns across two different color halftone images, employs dual conjugation in all three color channels, and considers inter-channel correlations. However, both the correct decoding rate for secret pattern extraction and the quality of generated halftone images require improvement.

Ding and Yang [19] introduced a new conjugate concept for color halftone images and applied it to both error-diffused and dot-diffused halftone images, proposing New Conjugate Color Error Diffusion (NCCED) and New Conjugate Color Dot Diffusion (NCCDD). The primary advantage of using new conjugation is that it reduces the number of components requiring permutation during color halftone information hiding, thereby decreasing instances where excessive permutation interference prevents data embedding. This approach improves the correct decoding rate (CDR) for secret image extraction and enhances the quality of generated halftone images. Experimental results demonstrate that for color halftone images, NCCDD and NCCED achieve the best performance.

To improve the convenience of secret information extraction, this paper focuses on halftone self-hiding algorithms based on error diffusion and dot diffusion, which hide a secret image within a single halftone image. Wu and Sun [23] proposed a dot-diffusion-based self-hiding algorithm for grayscale halftone images that can embed a secret image S within a dot-diffused halftone image. However,

this algorithm is limited to grayscale halftone images based on dot diffusion.

This paper implements a dot-diffused grayscale halftone self-hiding algorithm based on DHDCDD, extends it to error-diffused grayscale halftone images with algorithmic improvements, and proposes an error-diffused grayscale halftone self-hiding algorithm. Building upon the latest color halftone visual cryptography algorithms (NCCDD and NCCED), we further propose color halftone self-hiding algorithms for both dot-diffused and error-diffused halftone images.

1 Existing Work

Five major halftone visual cryptography algorithms are discussed in literature [15-19]: DHDCDD [15] for dot-diffused grayscale halftone images, DHDCED [16] for error-diffused grayscale halftone images, DCCDD [18] and NCCDD [19] for dot-diffused color halftone images, and NCCED [19] for error-diffused color halftone images.

The research objects of this paper include grayscale and color halftone images based on both dot diffusion and error diffusion. According to conclusions in [16], DHDCDD [15] and DHDCED [16] achieve the best performance for grayscale halftone images. Based on conclusions in [19], NCCDD [19] and NCCED [19] demonstrate the best performance for color halftone images. Therefore, these four algorithms serve as the foundation for this work. This paper investigates halftone self-hiding algorithms, with the self-hiding algorithm from [23] also serving as a research foundation.

Let X_1 and X_2 denote original images, Y_1 and Y_2 denote halftone images after information hiding, and S denote the secret image to be hidden.

1.1 DHDCDD and DHDCED

DHDCDD [15] and DHDCED [16] both employ dual conjugation to hide a secret image in two grayscale halftone images, with identical implementation processes differing only in their diffusion control methods: DHDCDD [15] uses dot diffusion while DHDCED [16] uses error diffusion. The implementation proceeds as follows:

- a) When $x_1(i,j)$ and $x_2(i,j)$ enter the system, diffusion errors are accumulated to generate $u_1(i,j)$ and $u_2(i,j)$.
- b) $u_1(i,j)$ and $u_2(i,j)$ undergo trial quantization to obtain trial quantization values $y_{1,trial}(i,j)$ and $y_{2,trial}(i,j)$, implemented through equations (1)-(3).
- c) The algorithm determines whether $y_{1,trial}(i,j)$ and $y_{2,trial}(i,j)$ satisfy the required conditions: when secret image data $s(i,j)$ is 0 (black), $y_2(i,j)$ must be conjugate to $y_1(i,j)$; when $s(i,j)$ is 1 (white), $y_2(i,j)$ must be

identical to $y1(i,j)$.

- d) If $y1,trial(i,j)$ and $y2,trial(i,j)$ meet requirement C, $u1(i,j)$ and $u2(i,j)$ are directly passed to $u1'(i,j)$ and $u2'(i,j)$ (i.e., $u1'(i,j) = u1(i,j)$ and $u2'(i,j) = u2(i,j)$).
- e) If $y1,trial(i,j)$ and $y2,trial(i,j)$ do not satisfy requirement C, permutation processing is required for either $y1,trial(i,j)$ or $y2,trial(i,j)$. Two permutation schemes exist: permuting $y1,trial(i,j)$ to calculate permutation interference $\Delta u1$, or permuting $y2,trial(i,j)$ to calculate $\Delta u2$. The scheme with smaller permutation interference Δu is selected.
- f) Calculation of $\Delta u1$ and $\Delta u2$ depends on permutation direction. If $y1,trial(i,j)$ or $y2,trial(i,j)$ changes from 255 to 0, equation (4) is used; if changing from 0 to 255, equation (5) is used.
- g) When $\min(\Delta u1, \Delta u2) \leq \text{threshold } T$, the direction with minimal interference is selected for permutation.
- h) When $\min(\Delta u1, \Delta u2) > T$, no permutation is performed, as excessive interference prevents information hiding at the current pixel.
- i) After processing the entire images X1 and X2 using the above procedure, halftone images Y1 and Y2 are generated.

The algorithm's advantage is its dual conjugation concept, but its limitation is applicability only to grayscale halftone images.

1.2 NCCDD and NCCED

Literature [19] defines a new conjugate concept (NC) for color halftone images, where NC values are calculated using equation (6). Here, Numof255 represents the number of color components equal to 255 among the three channels. If 2 or 3 components equal 255, the NC value is 1; if 0 or 1 component equals 255, the NC value is 0.

Let $y1(i,j)$ and $y2(i,j)$ represent two color halftone images. $NCy1(i,j)$ and $NCy2(i,j)$ denote their NC values. If $NCy1(i,j) \cdot NCy2(i,j) = 1$, $y1(i,j)$ and $y2(i,j)$ are new conjugates; if $NCy1(i,j) \cdot NCy2(i,j) = 0$, $y1(i,j)$ and $y2(i,j)$ are identical.

When $x1(i,j)$ and $x2(i,j)$ enter the system, trial quantization values $y1,trial(i,j)$ and $y2,trial(i,j)$ are calculated using equations (1)-(3). $NCy1,trial(i,j)$ and $NCy2,trial(i,j)$ are then computed using equation (6) to determine whether they match the required values. If not, permutation processing of $y1,trial(i,j)$ and $y2,trial(i,j)$ is necessary. Due to the new conjugate concept for information hiding, the permutation rules differ significantly from those in Section 1.1.

1.3 Grayscale Halftone Self-Hiding Algorithm Based on Dot Diffusion

Wu and Sun [23] proposed a dot-diffusion-based self-hiding algorithm for grayscale halftone images that can hide a secret image S within a dot-diffused halftone image. The main steps include:

- a) The original image X is divided into upper portion X_1 and lower portion X_2 . X has resolution $2W \times 2H$, while X_1 and X_2 each have resolution $W \times H$.
- b) Using a dot-diffusion-based halftone visual cryptography algorithm, secret pattern S is hidden in the halftone images generated from X_1 and X_2 , producing Y_1 and Y_2 .
- c) Y_1 and Y_2 are combined as upper and lower portions to form halftone image H .

Through this process, a secret image S is hidden within a single halftone image H . By dividing H into upper and lower portions and applying the extraction algorithm, secret pattern S can be recovered. Since halftone image H consists of two separate parts, this algorithm is suitable only for dot-diffused halftone images.

2 Main Contributions

This paper implements a dot-diffused grayscale halftone self-hiding algorithm based on DHDCDD, extends it to error-diffused grayscale halftone images with improvements, and proposes an error-diffused grayscale halftone self-hiding algorithm. Building upon the latest color halftone visual cryptography algorithms (NCCDD and NCCED), we propose color halftone self-hiding algorithms for both dot-diffused and error-diffused halftone images.

Figure 1 [Figure 1: see original paper] shows test images for the halftone self-hiding algorithms: Figures 1(a) and 1(b) are original grayscale and color images with 512×512 resolution; Figure 1(c) is the secret image to be hidden with 512×256 resolution.

2.1 Grayscale Halftone Self-Hiding Algorithm Based on Dot Diffusion

Using lena- 'gray' (Figure 1(a)) as the original grayscale image and Figure 1(c) as the secret image S , we apply the self-hiding algorithm described in Section 1.3 with DHDCDD [15] as the grayscale halftone visual cryptography algorithm to hide S in a dot-diffused halftone image. The generated halftone image is shown in Figure 2 Figure 2: see original paper with threshold $T=15$. The result demonstrates that the dot-diffusion-based grayscale halftone self-hiding algorithm successfully conceals secret pattern S within a dot-diffused grayscale halftone image.

2.2 Grayscale Halftone Self-Hiding Algorithm Based on Error Diffusion

1) Algorithm Implementation

Using lena- 'gray' (Figure 1(a)) as the original grayscale image and Figure 1(c) as secret image S , we follow the self-hiding algorithm flow from Section 1.3 but employ DHDCED [16] as the grayscale halftone visual cryptography algorithm to hide S in an error-diffused halftone image. The generated halftone image appears in Figure 2(b) with threshold $T=15$. While the algorithm successfully hides secret pattern S within an error-diffused grayscale halftone image, a noticeable horizontal line appears in the image center, significantly degrading halftone quality.

2) Cause Analysis

When using the self-hiding algorithm from Section 1.3, halftone image H consists of upper and lower portions. During the halftoning process, these two portions are strictly separated. Since error diffusion proceeds sequentially from top to bottom, this strict separation disrupts the continuous error diffusion process, resulting in a prominent horizontal line at the image center.

3) Improved Algorithm and Results

Combining the self-hiding algorithm from Section 1.3 with the improved algorithm shown in Figure 3 [Figure 3: see original paper] and using DHDCED [16] as the halftone visual cryptography algorithm, we hide secret image S in an error-diffused halftone image. The resulting halftone image is shown in Figure 4 [Figure 4: see original paper] with $T=15$. The improved self-hiding algorithm successfully eliminates the horizontal line defect.

Thus, integrating the self-hiding algorithm from Section 1.3 with the improvement described in Figure 3 enables an error-diffused halftone self-hiding algorithm. The complete process is detailed in Section 3.

2.3 Color Halftone Self-Hiding Algorithm Based on Dot Diffusion

Extending the algorithm from Section 1.3 from grayscale to color halftone images maintains the same flow, requiring only the adoption of color halftone visual cryptography algorithms. Using lena- 'color' (Figure 1(b)) as the original color image and following the self-hiding algorithm flow from Section 1.3 with NCCDD [19] as the color halftone visual cryptography algorithm, we hide secret image S in a dot-diffused color halftone image. The generated halftone image appears in Figure 5 Figure 5: see original paper with threshold $T=15$, demonstrating successful concealment of secret pattern S within a dot-diffused color halftone image.

2.4 Color Halftone Self-Hiding Algorithm Based on Error Diffusion

Extending the algorithm from Section 2.2 from grayscale to color halftone images maintains the same flow while requiring color halftone visual cryptography

algorithms. Using lena- 'color' (Figure 1(b)) as the original color image and following the self-hiding algorithm flow from Section 2.2 with NCCED [19] as the color halftone visual cryptography algorithm, we hide secret image S in an error-diffused color halftone image. The generated halftone image appears in Figure 5(b) with $T=15$, showing successful concealment of secret pattern S within an error-diffused color halftone image.

3 Halftone Self-Hiding Algorithms Based on Dot Diffusion and Error Diffusion

Based on the research in Section 2, this paper proposes halftone self-hiding algorithms using both dot diffusion and error diffusion. The implementation consists of two components: self-hiding algorithms on halftone images and self-extraction algorithms on halftone images.

3.1 Self-Hiding Algorithms on Halftone Images

Analysis in Section 2 reveals that the algorithm flows in Sections 2.1 and 2.3 are identical (for dot-diffused grayscale and color halftone self-hiding), as are the flows in Sections 2.2 and 2.4 (for error-diffused grayscale and color halftone self-hiding). Therefore, self-hiding algorithms on halftone images can be categorized into two types.

1) Dot-Diffusion-Based Self-Hiding Algorithm

Applicable to both grayscale and color dot-diffused halftone images, as shown in Figure 6 Figure 6: see original paper:

- a) Original image X is divided into upper portion X1 and lower portion X2. X has resolution $2W \times 2H$, while X1 and X2 each have resolution $2W \times H$.
- b) Using a dot-diffusion-based halftone visual cryptography algorithm, secret image S is hidden in the halftone images generated from X1 and X2, producing Y1 and Y2. For grayscale and color halftone images, DHDCDD [15] and NCCDD [19] are employed as the halftone visual cryptography algorithms, respectively.
- c) Y1 and Y2 are combined as upper and lower portions to form halftone image H.

2) Error-Diffusion-Based Self-Hiding Algorithm

Applicable to both grayscale and color error-diffused halftone images, as shown in Figure 6(b):

- a) Original image X is divided into upper portion X1 and lower portion X2. X has resolution $2W \times 2H$, while X1 and X2 each have resolution $2W \times H$.

- b) Using an error-diffusion-based halftone visual cryptography algorithm, secret image S is hidden in $X1$ and $X2$. The critical aspect of this process is obtaining the diffusion errors from the last two rows of $X1$. For grayscale and color halftone images, DHDCED [16] and NCCED [19] are employed as the halftone visual cryptography algorithms, respectively.
- c) The diffusion errors from the last two rows of $X1$ are combined with original $X2$ to form updated $X2$.
- d) The halftone visual cryptography algorithm is executed on original $X1$ and updated $X2$ to hide secret image S , generating new $Y1$ and new $Y2$.
- e) New $Y1$ and new $Y2$ are combined as upper and lower portions to form halftone image H .

Through processes 1) or 2), secret image S is hidden within a single halftone image. Since $Y1$ and $Y2$ each have resolution $2W \times H$, the resulting halftone image H has resolution $2W \times 2H$.

3.2 Self-Extraction Algorithms on Halftone Images

The self-extraction algorithm on halftone images is illustrated in Figure 7 [Figure 7: see original paper] and applies to both dot-diffused and error-diffused halftone images. The implementation flow is:

- a) A halftone image H is divided into upper portion $H1$ and lower portion $H2$. H has resolution $2W \times 2H$, while $H1$ and $H2$ each have resolution $2W \times H$.

For grayscale and color halftone images, the self-extraction algorithm operates in two modes:

For Grayscale Halftone Images (including both dot-diffused and error-diffused):

- a) The secret image D is extracted by performing XNOR operation on corresponding pixels in $H1$ and $H2$, as shown in equation (7).
- b) The correct decoding rate (CDR) of extracted secret image D is calculated using equation (8), where S represents the original secret image and both D and S have resolution $2W \times H$.

For Color Halftone Images (including both dot-diffused and error-diffused):

- a) $NCh1(i,j)$ and $NCh2(i,j)$ are calculated using equation (6).
- b) The secret image D is extracted using equation (9).
- c) The CDR of extracted secret image D is calculated using equation (8).

Through this process, a secret image with resolution $2W \times H$ can be extracted from a single halftone image.

4 Experimental Results

Figure 8 [Figure 8: see original paper] shows the experimental test images and secret pattern used in this paper. Figures 8(a)-(d) are grayscale test images, while Figures 8(e)-(h) are color test images, all with 512×512 resolution. Figure 8(i) is the secret image with 512×256 resolution.

Using the proposed algorithms, secret image S is hidden within a halftone image. Two scenarios are considered:

4.1 For Grayscale Halftone Images

Using Figures 8(a)-(d) as original grayscale images and Figure 8(i) as secret image S, the halftone self-hiding algorithm (Figure 6) hides S in four grayscale halftone images based on either dot diffusion or error diffusion. The self-extraction algorithm on halftone images (Figure 7) extracts secret image D using equation (7), and CDR is calculated using equation (8). Experimental results are shown in Table 2.

4.2 For Color Halftone Images

Using Figures 8(e)-(h) as original color images and Figure 8(i) as secret image S, the halftone self-hiding algorithm (Figure 6) hides S in four color halftone images based on either dot diffusion or error diffusion. The self-extraction algorithm (Figure 7) extracts secret image D using equations (6) and (9), and CDR is calculated using equation (8). Experimental results are shown in Table 2.

Through the above processes, the CDR for extracted secret images is obtained for all four halftone image types. Statistical CDR results for different parameters are presented in Table 2, where T represents the threshold for the entire image. For convenient comparison, average CDR values are calculated for each threshold, as shown in Table 3 and visualized in Figure 9 [Figure 9: see original paper].

From Table 3 and Figure 9, we conclude that under identical parameters using the proposed algorithms:

- a) CDR for secret images extracted from color halftone images is better than that from grayscale halftone images.
- b) CDR for secret images extracted from error-diffused halftone images is better than that from dot-diffused halftone images.
- c) Overall, the best performance is achieved for secret image extraction from error-diffused color halftone images.

5 Conclusion

This paper achieves halftone self-hiding algorithms based on dot diffusion and error diffusion by hiding a secret image within a single halftone image. Building upon the DHDCDD algorithm, we implement a dot-diffused grayscale halftone self-hiding algorithm, extend it to error-diffused grayscale halftone images with improvements, and propose an error-diffused grayscale halftone self-hiding algorithm. Based on the latest color halftone visual cryptography algorithms (NCCDD and NCCED), we propose color halftone self-hiding algorithms for both dot-diffused and error-diffused halftone images.

Experimental validation and performance comparison of the four self-hiding algorithms demonstrate that the proposed algorithms successfully achieve halftone self-hiding based on dot diffusion and error diffusion. Under identical parameters, the error-diffused color halftone self-hiding algorithm exhibits the best performance.

The proposed algorithms still have certain limitations. The self-hiding algorithms affect image quality to some extent. Future work will focus on improving halftone image quality while maintaining high correct decoding rates.

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