Difference expansion and prediction for high bit-rate reversible data hiding

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Abstract. Reversible data hiding deals with the insertion of auxiliary information into a host data without causing any permanent degradation to the original signal. In this contribution a high capacity reversible data hiding scheme, based on the classical difference expansion insertion algorithm, is presented. The method exploits a prediction stage, followed by prediction errors modification, both in the spatial domain and in the S-transform domain. Such two step embedding allows us to achieve high embedding capacity while preserving a high image quality, as demonstrated in the experimental results.

1 Introduction

Digital watermarking schemes are usually adopted for protecting rights of both digital data and their corresponding owners. Such methods invisibly embed a watermark into the data to be protected, thus allowing copyright protection and illegal copies or illegal distributors identification via the embedded information recovery. In particular, classical watermarking applications consist of copy control, broadcast monitoring, fingerprinting, authentication, copyright protection, and access control (see for instance Refs. 1 and 2). This technology can be used also for different purposes, such as multimedia indexing, enriching, quality assessment, error concealment, and others. In general, the imposed requirements are 1. robustness: the hidden data should be detectable after classical signal processing, 2. imperceptibility: the watermarked signal has to be perceptually similar to the original one, and 3. capacity: the number of bits that can be embedded should be as high as possible. In particular application scenarios (e.g., medical or military) another crucial constraint has to be considered 4. integrity of the recovered signal: the watermarking process has to be invertible, allowing the reconstruction of the original data after the watermark extraction. This last requirement is achieved by the so-called reversible watermarking techniques.

Many reversible watermarking algorithms have been proposed in the literature. The main difference among existing schemes lies in the particular method adopted for achieving reversibility. A first class of techniques exploits data compression, which was introduced in Ref. 5 by Fridrich et al. by embedding with the watermark also the lossless compressed original data as well as the corresponding location map. Celik et al. follow this idea in Ref. 6 by presenting a generalized-LSB data hiding method. Xuan et al. propose an algorithm based on integer wavelet transform.

Another class of methods is based on histogram shifting. The basic idea to embed the watermark through histogram modification was presented by Ni et al. 8 where the pixel values in the range between peak and zero points are modified. This technique is extended in, Ref. 9, where Hwang et al. propose to use two zero points and one peak point of the histogram as triplets to insert the data, and more
recently by Tai et al.\textsuperscript{10} Bo et al.\textsuperscript{11} and Yoo et al.\textsuperscript{12} to extend histogram shifting using small blocks of the image to embed data.

A third class of algorithms uses difference expansion to achieve reversibility. The first proposal is due to Tian\textsuperscript{13} and embeds the watermark by modifying the difference between a pair of pixels, thus exploiting the redundancy among neighboring pixel values. Following Tian’s intuition, many extensions were proposed, which extend this approach to triplets,\textsuperscript{14} quads,\textsuperscript{15} three-pixel blocks,\textsuperscript{16} or n-pixel blocks,\textsuperscript{17,18} therefore allowing a reduction of the location map and an increase in both efficiency and capacity. Further modifications are presented in Ref. 19 by Thodi et al.\textsuperscript{20} by Kamstra et al.\textsuperscript{21} by Hu et al.\textsuperscript{22} and by Chen et al.\textsuperscript{23}

Finally, a new idea based on pixel prediction is elaborated in a set of recent contributions. The median edge detector predictor is used by Thodi et al.\textsuperscript{24} by Hong et al.\textsuperscript{25} and by Yang et al.\textsuperscript{26} while the gradient adjusted prediction is exploited by Fallahpour et al.\textsuperscript{27} Kuribayashi et al.\textsuperscript{28} apply difference expansion and prediction, while Tsai et al.\textsuperscript{29} and Pan et al.\textsuperscript{30} apply predictive coding and histogram shifting in the specific domain of medical imaging. In Ref. 31, prediction and histogram shifting are dynamically applied depending on human visual system characteristic while in Refs. 32 to 34, interpolation is used as prediction to calculate the error band. Xuan et al.\textsuperscript{35} and Kuo et al.\textsuperscript{36} apply error control and histogram shifting to embed data keeping good stego-image quality. Tseng et al.\textsuperscript{37} study various predictors, while Hu et al.\textsuperscript{38} improve the location map compressibility, Sachnev et al.\textsuperscript{39} reduce its size, and Fujiyoshi et al.\textsuperscript{40} avoid any image-dependent parameter or location map. In Ref. 41, Yang et al. propose a data hiding technique in both the spatial and frequency domain which seems to be robust against JPEG and JPEG2000. In this context, the authors proposed in Ref. 42 to exploit both local dependency and non-local similarity for prediction, by employing block-matching techniques, while in Ref. 43 histogram shifting was combined with a particular prediction exploiting directional differences.

In this work a double embedding scheme is proposed, where a prediction stage, followed by prediction errors modification, is applied both in the spatial domain and in the S-transform domain. The adoption of this multilayer approach allow us to achieve very high capacity while preserving good image quality. A preliminary study on multi-resolution approaches was presented in Ref. 44 recently, high capacity was achieved by in Refs. 45 and 46, which we compare the performances with in the experimental section.

The rest of the work is organized as follows: details on the proposed algorithm are given in Sec. 2, while the experimental results are reported in Sec. 4, and finally in Sec. 5 some conclusions are drawn.

### 2 Embedding

As depicted in Fig. 1 the proposed scheme works as follows:

1. Prediction is applied to the original image \(X = \{x_{ij}\}\), \(j = 1, \ldots, n\) in the spatial domain, thus obtaining \(\hat{X}\) as described in Sec. 2.1 and correspondingly the spatial prediction error

\[
E_{sp} = X - \hat{X}.
\] (1)

2. Embedding via difference expansion into prediction error \(E_{sp}\) as detailed in Sec. 2.4:

- Definition of positions used for embedding and of the corresponding location map (required at the detector side to perform watermark extraction and original image reconstruction).
- Watermark and overhead information embedding thus defining a new watermarked prediction error \(E'_{sp}\).

The watermarked image \(X'\) is defined as follows

\[
X' = \hat{X} + E'_{sp}.
\] (2)

3. S-transform is applied to the watermarked image \(X'\), thus obtaining low-and high-frequency bands \(L\) and \(H\), respectively (see details in Sec. 2.2). Starting from \(L\), prediction is applied to get \(\hat{H}\) and the transform prediction error is calculated as follows

\[
E_{tr} = H - \hat{H}.
\] (3)

4. Embedding via difference expansion into prediction error \(E'_{tr}\) defining a new watermarked prediction error \(E''_{tr}\) as in step 2. The watermarked high-frequency band \(H''\) is defined as follows

![Fig. 1 Proposed scheme for watermark embedding.](image-url)
\[ H' = \hat{H} + E'_w. \] (4)

5. Finally, the inverse S-transform is applied to \( L \) and \( H' \) to obtain the watermarked image \( X' \).

Let us notice that the watermark and the required overhead information are embedded into two steps (2 and 4) and will be denoted as \( W = (W_{sp}, W_u) \).

### 2.1 Prediction in Spatial Domain

The gradient adjust predictor (GAP)\(^27\) considers seven neighbors of the to-be-predicted pixel \( \hat{x}_{i,j} \) as follows:

\[
\begin{align*}
    d_x &= |x_{i-1,j} - x_{i-1,j-1}| + |x_{i,j-1} - x_{i,j-2}| \\
    &+ |x_{i+1,j} - x_{i+1,j-2}| \\
    d_h &= |x_{i-1,j} - x_{i-2,j}| + |x_{i,j-1} - x_{i-1,j-1}| + |x_{i,j-1} - x_{i+1,j-1}| \\
    D &= d_x - d_h \\
    \hat{x}_{i,j} &= \frac{x_{i-1,j} + x_{i,j-1} + x_{i+1,j} + x_{i,j-1} - x_{i-1,j-1}}{4} \\
    \hat{x}_{i,j} &= \left\{ \begin{array}{ll}
        \frac{x_{i,j-1} + x_{i-1,j-1}}{2} & \text{if } D < -80 \\
        \frac{3x_{i,j-1} + x_{i-1,j-1}}{4} & \text{if } -80 \leq D < -32 \\
        \frac{2x_{i,j-1} + x_{i-1,j-1}}{4} & \text{if } -32 \leq D < -8 \\
        \frac{x_{i,j-1} + x_{i-1,j-1}}{2} & \text{if } -8 \leq D < 8 \\
        \frac{3x_{i,j-1} + x_{i-1,j-1}}{4} & \text{if } 8 \leq D < 32 \\
        \frac{2x_{i,j-1} + x_{i-1,j-1}}{4} & \text{if } 32 \leq D < 80 \\
        x_{i,j} & \text{if } D \geq 80
    \end{array} \right.
\end{align*}
\] (5)

This defines \( \hat{X} = \{ \hat{x}_{i,j} \}, i,j = 1, \ldots, n \) and the spatial prediction error \( E_{sp} = X - \hat{X} \) that will be used for watermark embedding via difference expansion.

### 2.2 S-Transform

The S-transform\(^27\) is an invertible time-frequency spectral localization technique often called also integer Haar wavelet transform. Let us consider the image \( X' \) of size \( n \times n \). The low-frequency \( L \) and the high-frequency \( H \) sub-band decomposition of \( X \) can be computed as follows:

\[
\begin{align*}
    I_{i+1,j} &= \frac{x_{i+1,j} + x_{i+1,j-1}}{2} \\
    H_{i+1,j} &= x_{i+1,j} - x_{i+1,j-1}. \quad (6)
\end{align*}
\]

where \( i = 0, \ldots, \frac{n}{2} - 1, j = 1, \ldots, n \) and \( L = \{ I_{i,j} \} \) while \( H = \{ h_{i,j} \} \). The corresponding inverse transformation is given by

\[
\begin{align*}
    x_{i+1,j} &= I_{i+1,j} + \frac{h_{i+1,j} + 1}{2} \\
    x_{i+1,j} &= x_{i+1,j} - h_{i+1,j}. \quad (7)
\end{align*}
\]

Notice that in this case we are applying the S-transform in the vertical direction. Horizontal decomposition can be performed just by defining \( L = \{ I_{i,j+1} \} \) and \( H = \{ h_{j,i+1} \} \).

### 2.3 Prediction in Transform Domain

To guarantee the reversibility of the watermarking method, the proposed prediction scheme aims at predicting high-frequency sub-band starting from the low frequency one in a way all required information will be available also at the detection side. The prediction scheme can be summarized as follows. Given the low frequency coefficients we define relative differences

\[
\Delta l_{i+1,j} = l_{i,j} - l_{i+1,j}, \quad (8)
\]

where \( i = 1, \ldots, \frac{n}{2} - 1 \). Notice that differences can be calculated starting from the second row, thus we impose \( \Delta l_{1,j} = 0 \). The predicted high-frequency sub-band \( \hat{H} \) is estimated as following:

\[
\hat{h}_{i+1,j} = \frac{1}{4} l_{i,j} + \frac{1}{8} l_{i+1,j} - \frac{3}{2} l_{i+2,j} + \frac{1}{8} l_{i+3,j}, \quad (9)
\]

where \( i = 1, \ldots, \frac{n}{2} - 3, j = 1, \ldots, n \). This defines the transform prediction error \( E_{tr} = \{ e_{i+1,j} \} \) that will be used for watermark embedding via difference expansion.

### 2.4 Embedding Via Difference Expansion

The main idea of difference expansion is to hide information into a set of values, in two slightly different ways according to their characteristics. Once \( E_{sp} \) and \( E_{tr} \) are defined, the watermark \( W = (W_{sp}, W_u) \) insertion is performed by applying Tian’s method\(^12\) to \( E_{sp} \) and \( E_{tr} \), thus defining the watermarked prediction error \( E_{wp} \) and \( E_{wt} \), used in Eqs. (2) and (4), respectively. For simplicity and coherence with the original Tian’s method we describe the process in the transform domain but the same procedure is applied in the spatial domain.

In particular, following Eq. (4) \( E'_w \) is used to define the watermarked values of \( H' \) (similarly \( E'_{sp} \) allows to define the watermarked values of \( X' \)), which have to satisfy following rules in order to avoid overflow and underflow problems. Indeed, \( X, X' \), and \( Z' \) values should be bounded in the range [0, 255]

\[
\begin{align*}
    0 \leq l_{i+1,j} + \frac{h'_{i+1,j} + 1}{2} &\leq 255 \\
    0 \leq l_{i+1,j} - \frac{h'_{i+1,j}}{2} &\leq 255. \quad (11)
\end{align*}
\]

Since both \( l \) and \( h' \) are integer values

\[
\begin{align*}
    |h'_{i+1,j}| &\leq 2(255 - l_{i+1,j}) = a, \\
    |h'_{i+1,j}| &\leq 2l_{i+1,j} + 1 = b. \quad (12)
\end{align*}
\]

Now we can define two different types of values in \( E_{tr} \) (similarly in \( E_{sp} \)):
The error is expandable if for both the watermark entries \( w_m = 0 \) and \( w_m = 1 \)

\[
|h'_{i+1,j}| = |\hat{h}_{i+1,j} + e'_{i+1,j}| \leq \min(a, b). \tag{13}
\]

In this case we can perform the embedding of the bit \( w_m \) of the watermark \( W \) by expanding the error and define the watermarked value as follows:

\[
e'_{i+1,j} = 2e_{i+1,j} + w_m. \tag{14}
\]

The error is changeable if for both the watermark entries \( w_m = 0 \) and \( w_m = 1 \)

\[
|h'_{i+1,j}| = |\hat{h}_{i+1,j} + \frac{e_{i+1,j}}{2} + w_m| \leq \min(a, b). \tag{15}
\]

In this case embedding is performed just by substituting the least significant bit (LSB) of \( e_{i+1,j} \) with the bit \( w_m \) of the watermark \( W \).

Notice that an expandable value is also changeable, as depicted in Fig. 2(a). Therefore, it can be used in both ways. This property will be exploited in the following subsets definition. Indeed, before embedding error values are partitioned into four sets:

- \( E1 \) which contains all expandable differences with \( e_{i+1,j} = 0 \) or \( e_{i+1,j} = -1 \).
- \( E2 \) which contains all expandable differences that do not belong to \( E1 \) and are used as expandable.
- \( E3 \) which contains all expandable differences that do not belong to \( E1 \) and are used as changeable.
- \( C \) which contains all changeable differences that do not belong to \( E1 \) or \( E2 \) or \( E3 \).
- \( NC \) which contains all non-changeable differences.

Embedding is now performed in \( E1 \cup E2 \) and \( E3 \cup C \) following the two different rules, expansion and LSB substitution, respectively.

### 2.5 Overhead Information

In order to design a reversible method some information must be sent to the detector: such extra information is composed by original LSB of every error value changed through LSB substitution, and the so-called location map that is used to identify the positions of the bits that have been modified and the particular embedding adopted. The location map is a binary matrix of same size of the original image with value 1 in the position corresponding to differences belonging to \( E1 \cup E2 \) and with value 0 in the position belonging to \( E3 \cup C \cup NC \) [see Fig. 2(a)]. It is worth noticing that a changeable value remains changeable also after embedding, thus it is always distinguishable from a value in NC. This way, during the detection stage it is possible to distinguish places where a bit of mark was introduced, and where not [see Fig. 2(b)].

The location map is lossless compressed defining the overhead information \( LM \) which has to be sent to the detector together with the mark. The compression ratio depends on the applied technique and affects the capacity of the algorithm. For each value of \( e_{i+1,j} \) in \( E3 \) and \( C \), LSB values have to be collected since bit insertion change them. Such values are stored into a bit-stream called LSB. Therefore, the complete stream \( W = \{W_{sp}, W_{tr}\} \) is embedded consists of \( LM \cup LSB \cup \) watermark for both \( W_{sp} \) and \( W_{tr} \). Thus, the watermark payload size is defined depending on the size of \( E2 \) and on the compression rate of the location map.

### 3 Detection

Let us now describe in detail all phases of the detection process, illustrated also in Fig. 3:

1. The S-transform is applied to the watermarked image \( X'' \), resulting in \( L \) and \( H' \) decomposition.
2. Starting from \( L \), prediction is applied thus recovering \( \hat{H} \). The modified prediction error is calculated as

\[
E'_{tr} = H' - \hat{H}. \tag{16}
\]

Since the \( L \) sub-band coefficients used for predicting \( \hat{H} \) have not been modified (bitwise equal), the predicted \( \hat{H} \) is exactly the same as in the embedding phase. Thus, information extracted from \( E'_{tr} \) is bitwise identical to the one inserted (thanks to the reversibility of the difference expansion method, see for instance Ref. 13).
3. Bit-stream \( W_{tr} \) is extracted from \( E'_{tr} \) from all changeable values. Now from the recovered \( LM \) it is possible to differentiate among differences used as expandable \( E1 \cup E2 \), changeable \( E3 \cup C \), and non-changeable \( NC \). From LSB it is then possible to recover all original LSB values of changeable differences. Finally, the watermark can be extracted and all original values of \( E_{tr} \) can be restored. The original high-frequency sub-band \( H \) can be recovered by calculating.
\[
H = \hat{H} + E_w.
\]  
(17)

4. The image \(X'\) can be restored by computing the inverse S-transform of \(L\) and \(H\).

5. Starting from \(X'\), prediction is applied thus recovering \(\hat{X}\). The modified prediction error is calculated as

\[
E_{sp}' = X' - \hat{X}.
\]  
(18)

Also in this case, prediction is defined in order to be reversible: starting from the same input, the predicted set of coefficients will be exactly the same, independently from coefficients modified by the watermark (inserted only into high frequencies), see for instance Ref. 27.

6. Bit-stream \(W_{sp}\) is extracted from \(E_{sp}'\) as in step 3 and all original values of \(E_{sp}\) can be restored. Finally, the original image \(X\) can be recovered by calculating

\[
X = \hat{X} + E_{sp}.
\]  
(19)

Since both extraction steps (3 and 5) are reversible, the whole process can be inverted and the original image bitwise perfectly recovered.

4 Experimental Results

To evaluate the effectiveness of the proposed schemes several experimental tests have been performed. The achieved results are reported by considering both capacity (payload of the watermark inserted without considering the overhead information: location map bit-stream LM and LSB of differences used as changeable, as described in Sec. 2.5), measured in bit per pixel (bpp) and quality of the watermarked image measured with different perceptual metrics: PSNR, PSNR-HVS, and PNSR-HVS-M. All tests have been computed on a set of 32 images taken from the GrayScale Set 2 image repository of the University of Waterloo (http://links.uwaterloo.ca/Repository.html) and the Tampere Image Database 2008 (http://www.ponomarenko.info/tid2008.htm), considering the gray-scaled version of original images only.

Although the reversibility of the exploited techniques is already proved in the literature (see for instance Ref. 27), first of all we have verified that both the original image and the embedded data can be perfectly recovered from the watermarked one, after the hidden information extraction procedure.

As far as the spatial prediction is concerned, different types of prediction have been tested and combined with the prediction in the transform domain described in Sec. 2.3. In Figs. 4 to 7 results are reported for six different well known spatial predictors: GAP, median edge detector (MED), DARK, PAETH, simple average (SA), and previous pixel (DIFF). In all cases (we report here results for four images) GAP gives the best results and this motivates our choice in the algorithm design.

Results reported in Figs. 8 to 11 present the detailed performances achieved by the proposed method for four images.
Fig. 6 Spatial predictors performances in terms of PSNR for the Boat image.

Fig. 7 Spatial predictors performances in terms of PSNR for the Goldhill image.

Fig. 8 Performances of the proposed approach in terms of different perceptual metrics for the Lena image.

Fig. 9 Performances of the proposed approach in terms of different perceptual metrics for the Barbara image.

Fig. 10 Performances of the proposed approach in terms of different perceptual metrics for the Boat image.

Fig. 11 Performances of the proposed approach in terms of different perceptual metrics for the Goldhill image.
Table 1 Maximum capacity and corresponding quality of watermarked images for the whole dataset.

<table>
<thead>
<tr>
<th>Image</th>
<th>Max payload (bpp)</th>
<th>PSNR (dB)</th>
<th>PSNR-HVS-M (dB)</th>
<th>PSNR-HVS (dB)</th>
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</tbody>
</table>

(due to lack of space) in terms of different quality metrics: PSNR, PSNR-HVS, and PNSR-HVS-M. This way, we do not only have the information about classical PSNR measure of quality but also about state-of-art perceptual quality metrics which allow to better understand the real user evaluation of distortion introduced with the watermark. It is worth noticing that the proposed method allows us to achieve high capacity by keeping the quality of the watermarked images pretty high. With respect to Ref. 45, we achieve better results: for example, for Lena images pretty high. With respect to Ref. 46 is concerned, the proposed technique achieves very similar results for high-capacity ranges (see for example Lena and Barbara images). Comparison with high-capacity techniques cannot be done in terms of perceptual quality metrics due to the fact that results are usually reported just in terms of PSNR.

The maximum capacity achieved and the corresponding perceptual quality of the watermarked image in terms of the three metrics are shown in Table 1 for all 32 tested images. It is evident that the proposed technique allows us to embed a high number of bits for the watermark without impacting too much on the quality of the data. In particular, capacity higher that 1 bpp can be achieved for Mandrill whereas Refs. 45 and 46 present maximum capacity lower than 1 bpp.

5 Conclusions

In this work a reversible data hiding method has been presented. It is based on the combination of prediction and difference expansion insertion algorithms and on the use of such combination both in the spatial and in the transform domain. The adoption of a multilayer technique results in high capacity and good image quality as demonstrated in the performed simulations.

References


are focused on image and video processing, with particular attention to data hiding and multimedia quality assessment.

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