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A recent survey of reversible watermarking techniques

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ABSTRACT

The art of secretly hiding and communicating information has gained immense importance in the last two decades due to the advances in generation, storage, and communication technology of digital content. Watermarking is one of the promising solutions for tamper detection and protection of digital content. However, watermarking can cause damage to the sensitive information present in the cover work. Therefore, at the receiving end, the exact recovery of cover work may not be possible. Additionally, there exist certain applications that may not tolerate even small distortions in cover work prior to the downstream processing. In such applications, reversible watermarking instead of conventional watermarking is employed. Reversible watermarking of digital content allows full extraction of the watermark along with the complete restoration of the cover work. For the last few years, reversible watermarking techniques are gaining popularity because of its increasing applications in some important and sensitive areas, i.e., military communication, healthcare, and law-enforcement. Due to the rapid evolution of reversible watermarking techniques, a latest review of recent research in this field is highly desirable. In this survey, the performances of different reversible watermarking schemes are discussed on the basis of various characteristics of watermarking. However, the major focus of this survey is on prediction-error expansion based reversible watermarking techniques, whereby the secret information is hidden in the prediction domain through error expansion. Comparison of the different reversible watermarking techniques is provided in tabular form, and an analysis is carried out. Additionally, experimental comparison of some of the recent reversible watermarking techniques, both in terms of watermarking properties and computational time, is provided on a dataset of 300 images. Future directions are also provided for this potentially important field of watermarking.

1. Introduction

OVER the past few years, the enormous increase in the use of digital content has increased the issues such as online data vulnerability and copyrights violation [7,10,23,50,81]. One of the prominent solutions is the watermarking of the digital content. Beside watermarking, there exist other interesting methods that can also provide protection to the digital content e.g., cryptography, steganography etc. [13,29,48,58,65,111]. Steganography and watermarking both come under data hiding techniques i.e., they are used to hide secret information in the cover work. However, there exist subtle difference between steganography and watermarking i.e. steganography conceals the very existence of secret information. If the existence of secret information is revealed, steganography fails. Whereas, in watermarking the existence of secret information can be

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known [23]. Ideally, the goal of watermarking is to make the removal/manipulation of secret information impossible. In contrast, cryptography does not conceal the existence of secret information, rather it encrypts the information in such a way that it appears useless to a pirate unless decrypted with the appropriate key [10,23].

Through suitable watermarking techniques, the protection of the data can be ensured and one can know whether the received content has been tampered with or not. However, watermarking can cause damage to the sensitive information present in the cover work, and thus at the receiving end, the exact recovery of cover work may not be possible. In some applications, even the slightest distortion in the cover work is intolerable. For example, in the field of medical imagery, if a medical image is modified using conventional watermarking, the small change may affect the interpretation significantly and a physician may make a wrong diagnosis. Similarly, in case of military application, changes due to embedding of secret information can substantially alter the cover image and therefore, the decision taken may cost considerably. Consequently, there is a strong need to restore the cover work to its original form. Reversible watermarking, also known as lossless watermarking, allows full extraction of the embedded information along with the complete restoration of the cover work. Reversible watermarking can thus be considered as a special case of watermarking.

Reversible watermarking is gaining more attention for the last few years because of its increasing applications in military communication, healthcare, and law-enforcement. Fig. 1 shows the block diagram of a basic reversible watermarking system.

In the sequel, the terms information-to-be-embedded and watermark are used interchangeably. As regards general watermarking schemes, different types are reported in literature; namely robust, fragile, and semi fragile [11,12,14,25,34,37,39,49,57,70,74,104]. In robust watermarking schemes, watermark is designed to survive normal image processing operations. While, in fragile watermarking schemes, watermark breaks if the watermarked work undergoes any kind of modification, thus it is useful for authentication of digital media [94,109]. Whereas, in case semi-fragile watermarking schemes, watermark needs to survive minor modifications. These different types of watermarking schemes have different applications, and thus are used according to the nature of application. But, the existing reversible watermarking schemes are mostly fragile in nature. The two important properties of reversible watermarking are imperceptibility and embedding capacity. Roughly speaking, imperceptibility is the measure of similarity between watermarked and the cover image. While, embedding capacity is the measure of the maximum number of information bits that can be embedded in the cover image. The performance of a reversible watermarking technique is thus evaluated on the basis of these measures.

One of the first reversible watermarking method was introduced by Honsinger et al. [41]. They utilized modulo addition 256 to achieve reversibility in their watermarking technique. Macq [69] developed a reversible watermarking approach by modifying the patchwork algorithm and using modulo addition 256. Although, Honsinger et al. [41] and Macq [69] proposed reversible techniques, the imperceptibility of their approaches is not impressive. The watermarked images resulting from Honsinger et al. [41] and Macq [69] ‘s techniques suffer from salt and pepper noise because of the use of modulo addition 256. A reversible watermarking technique without using modulo addition 256 was then introduced by Fridrich et al. [30]. Fridrich et al. [30] proposed the concept of compressing the least significant bit (LSB) plane of cover image to make space for the watermark to be embedded. However, the embedding capacity of this approach was limited. To improve the embedding capacity and imperceptibility of the watermarked image, Fridrich et al. [31] then proposed another approach. Evolution of reversible watermarking started around 2000, and it is now quite difficult to keep up with the development that is going on in this field. Many reversible watermarking algorithms have been developed in the past decade. A number of new techniques, extensions or improved versions of the earlier techniques, have been proposed in recent years. The improvement is primarily based upon making a good imperceptibility versus capacity tradeoff.

Zheng et al. reported a comprehensive survey on robust image watermarking alogorithms [114]. Guo [35] and Guo et al. [36] reported reversible watermarking techniques for the halftone images. In past, reviews of different reversible watermarking techniques were also carried out [8,28,83]. Feng et al. [28] discussed key requirements of the watermark and classified reversible watermarking schemes into three categories: data compression, difference expansion and histogram shifting. A single reversible watermarking scheme is discussed in each of these categories. Some major challenges faced by the researchers in this field are also outlined. Pan et al. [83], categorized various reversible watermarking approaches into two classes; additive and substitution, based on embedding method. Comparison is carried out through empirical analysis of selected reversible watermarking approaches on medical images. Caldelli et al. [8] provided another review, which classifies reversible watermarking techniques, on the basis of watermarking properties, i.e., into robust, fragile and semi-fragile.

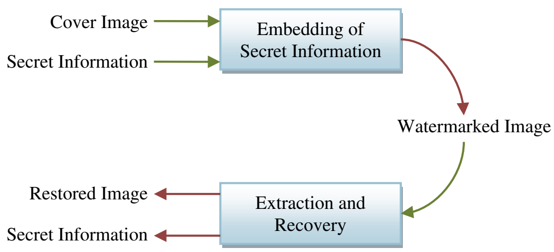

Fig. 1. Basic reversible image watermarking scheme.

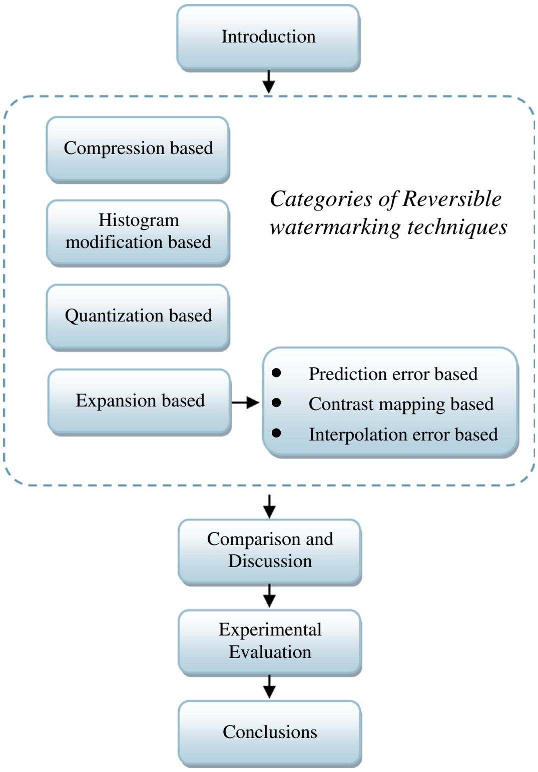

Fig. 2. Classification of reversible watermarking approaches.

Caldelli et al. [8] also performed classification according to the watermark embedding domain i.e. spatial or frequency domain. The aforementioned review articles were quite valuable; however, they cover very limited area and discuss only few of the works in the field of reversible watermarking. The prospective reversible watermarking approaches based on the concept of error expansion have recently been reported in large numbers, and they mostly outperform other types of reversible watermarking approaches. Most of these new and efficient prediction error based reversible watermarking techniques are not covered by the aforementioned reviews. Additionally, there has been a rapid increase in the applications of reversible watermarking techniques. Consequently, a recent review of newly emerging reversible watermarking techniques is highly desirable.

In this survey paper, we thus review in detail (through block-diagrams, tabular-comparisons, and actual performance-comparisons) the newly emerging reversible watermarking techniques. Although different categories of reversible watermarking techniques are reported in literature, it is hard to draw a precise boundary among the different categories of reversible watermarking techniques. However, one thing common in all of these approaches is to create some space for hiding information. We reviewed newly emerging reversible watermarking techniques and categorized them into four groups, i.e. compression based, histogram modification based, quantization based, and expansion based techniques. We briefly analyze the first three groups; while the expansion based reversible watermarking is discussed in detail. The reason is that error expansion based reversible watermarking techniques are quite promising in achieving high capacity at a given image quality measure, and are computationally efficient. To this end, several expansion based watermarking techniques are discussed and compared.

The organization of this survey paper is presented through a block diagram in Fig. 2 to provide a brief overview. Section 2 first presents a short review of compression based reversible watermarking techniques. Section 3 then analyzes histogram modification based reversible watermarking techniques. Next, quantization based reversible watermarking techniques are discussed in Section 4, while Section 5 presents detailed review of expansion based reversible watermarking. Comparison and experimental evaluation of different reversible watermarking techniques is presented in Sections 6 and 7, respectively. Finally, Section 8 concludes this article and provides some future directions.

2. Compression based reversible watermarking

In order to recover the original image, we need to store the information essential for recovery of the original image along with the watermark. Thus, in case of reversible watermarking, additional data needs to be embedded and consequently,

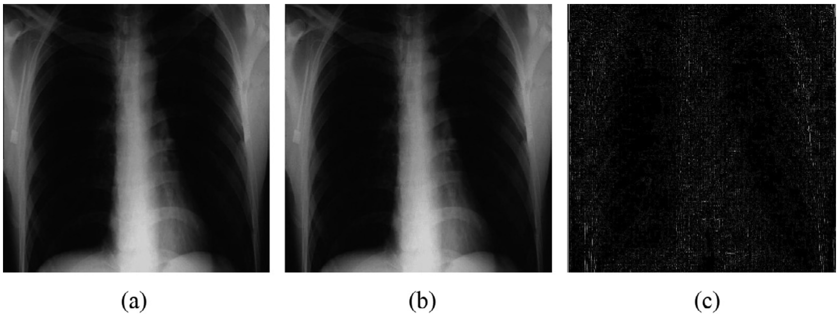

Fig. 3. (a) Chest X-ray Image. (b) Watermarked Image using Arsalan et al.'s [6] scheme with PSNR = 42.72 dB, and embedding capacity of 0.7 bpp. (c) Enhanced difference of (a) and (b).

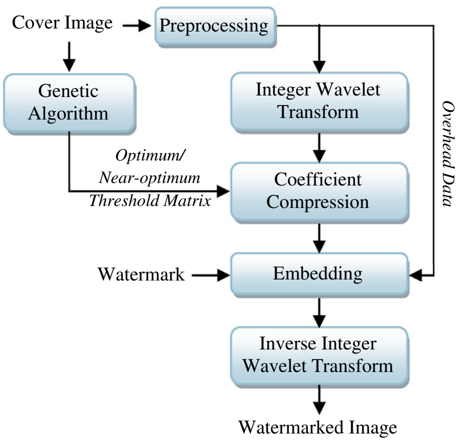

Fig. 4. Arsalan et al.'s [6] companding based intelligent reversible watermarking approach.

needs more space compared to conventional watermarking for data embedding. A simple approach will be to compress a part of cover image for embedding data. Several reversible watermarking schemes are reported using this approach.

In 2004, Yang et al. [110] proposed a high capacity companding technique for image watermarking in discrete cosine transform domain. Whereby, twice-try based block discrimination structure is incorporated to overcome overflow/underflow problem. Celik et al. [9] in 2005 proposed a well known compression based approach. The intensity values of pixels in the cover image are first quantized by applying L-level scalar quantization. Then, the remainders obtained are compressed using a context based adaptive lossless image codec (CALIC), and watermark information is concatenated with it. In the end, the data to-be-embedded is added to the quantized image to obtain the watermarked image. Xuan et al. [108] developed a reversible watermarking technique using companding function on integer wavelet coefficients. Companding function is used to compress the coefficients whose values are greater than a certain threshold. This process results in an increase in the embedding capacity. However, it also increases the auxiliary data. Memon et al. [71] applied simple threshold optimization to improve the capacity of Xuan et al.'s approach [108].

On the other hand, Arsalan et al. [6] utilized Xuan et al.'s [108] companding function in combination with genetic algorithm to develop a high capacity reversible watermarking technique. In their approach, image is first transformed into frequency domain by taking integer wavelet transform and then divided into blocks. Companding operation is performed on each coefficient of a block, whose value is greater than a certain threshold. Each block has its own threshold value. An Optimal/near-optimal threshold matrix is evolved using genetic algorithm, and is embedded as auxiliary information. Arsalan et al.'s [6] technique provides good performance in terms of capacity versus imperceptibility tradeoff, but consumes more time in training phase. Additionally, the genetic algorithm based optimization has to be performed for every cover image. Fig. 3 shows the cover, watermarked and difference images for Arsalan et al.'s approach. The block diagram of Arsalan et al. 's [6] scheme is shown in Fig. 4.

3. Histogram modification based reversible watermarking

Many researchers have carried out research in the field of histogram modification based reversible watermarking [32,43,46,47,52,56,60,63,64,76,77,82,91,96,102,103]. Initially, Vleeschouwer et al. [103] presented circular interpretation based reversible watermarking. In their approach, image is divided into several blocks of neighboring pixels. Then, each block is split into two zones, and corresponding histograms are calculated. A bin is shifted in accordance with the value of corresponding watermark bit. If the bit is '1', shift the lowest bin to the highest one, and downgrade other bins. And if the bit is '0', then upgrade each bin and shift the highest bin to the lowest bin. Later, Vleeschouwer et al. [103] improved their work by introducing bijective transformation [102]. The high distortion caused by the shift of lowest and highest bin is handled by allowing at most two shifts.

In 2006, Ni et al. [76] developed a novel reversible watermarking approach based on image histogram modification. Before embedding, a pair of peak and zero points is selected from the histogram of the cover image. Only pixels with values between peak and zero points undergo modification during embedding process. However, the embedding capacity is restricted to the number of pixels present in the peak point in a histogram of the cover image.

To increase the embedding capacity of histogram based reversible watermarking techniques, different algorithms are reported. Lin et al. [64] presented a multilevel reversible watermarking approach that utilizes the histogram of difference image for data embedding. The difference image is generated by taking the difference of two adjacent pixels of the cover image. The cover image is divided into a number of non-overlapping blocks, and then the difference block corresponding to each image block is generated. For data embedding, histogram modification method is applied to each difference block. But this technique suffers from large amount of overhead data i.e. storing the peak value information for each block.

In another work, Ni et al. [77] extensively investigated the Vleeschouwer et al. approach [102]. They concluded that this technique uses modulo-256 addition to tackle overflow and underflow problems, which causes salt and pepper noise. Ni et al. [77] thus proposed an approach, which does not suffer from salt and pepper noise. Gao et al. [32] then highlighted the shortcomings of Ni et al.'s approach [77] and improved it. Fig. 5 shows the block diagram of Gao's et al.'s [32] method.

Tsai et al. [96] proposed a subtly different approach from [64]. The difference between a basic pixel and every other pixel in the block is used rather than the difference of adjacent pixels. However, the prediction method used in [96] is less accurate, and the need for keeping the values of the basic unchanged pixels reduces the embedding capacity of the scheme. Kim et al. [52] proposed a novel method that exploits the spatial correlation between sub-sampled images. A reference sub-sampled image is first selected from several sub-sampled images, and then differences between reference and other sub-sampled images are generated. Embedding is then performed by modifying the difference histogram.

Kamran et al. [47] improved the work reported by Gao et al. [32] by proposing the embedding of correct message bit only. Due to this improvement, BCH coding and permutation scheme is not required which increases the watermark embedding capacity. Kamran et al. [47] also reported a novel approach which utilizes the concept of down sampling for performance improvement. Down sampling provides two sub-sampled versions of the cover image i.e., reference and data hiding. Then the blocks are generated by using these two sub-sampled versions. Embedding is carried out in the blocks through histogram modification. Further, to make the technique a blind one, Kamran et al. [47] embedded the location map (LM) in the watermarked image. Fig. 6 shows block diagram of the embedding process, and the corresponding watermarked image of Kamran et al. 's approach [47] is shown in Fig. 7.

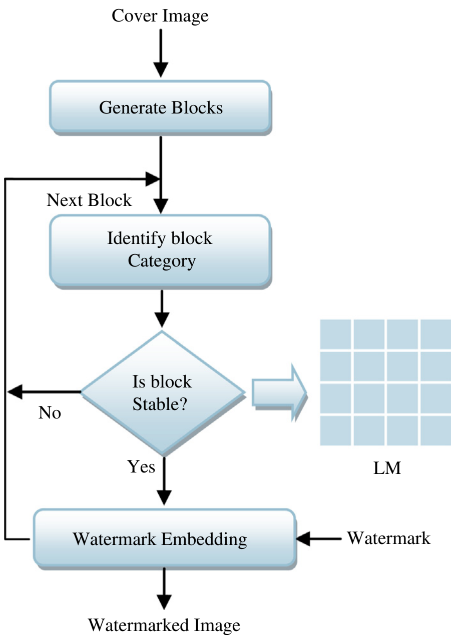

Fig. 5. Block diagram of the embedding procedure of Gao et al.'s [32] histogram modification based reversible watermarking.

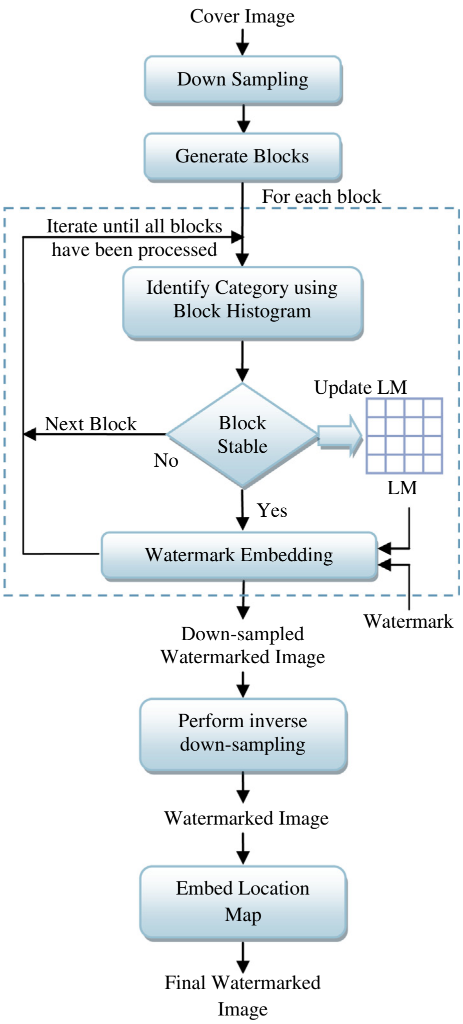

Fig. 6. Block diagram of the embedding procedure of Kamran's [47] histogram modification based reversible watermarking approach.

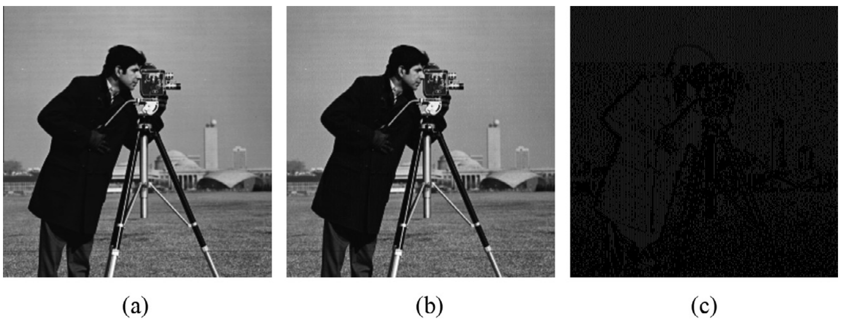

Fig. 7. (a) Cameraman Image. (b) Watermarked Image using Kamran et al.'s [47] scheme with PSNR = 41.65 dB, and embedding capacity of 0.8 bpp. (c) Enhanced difference of (a) and (b).

Some robust semi-blind reversible watermarking techniques employing statistical quantity histogram are also reported in literature [4,5,33]. An et al. [4] presented a semi-blind robust reversible watermarking scheme, which utilizes statistical quantity histogram shifting for embedding, and the extraction procedure is modeled as a classification problem in integer wavelet domain.

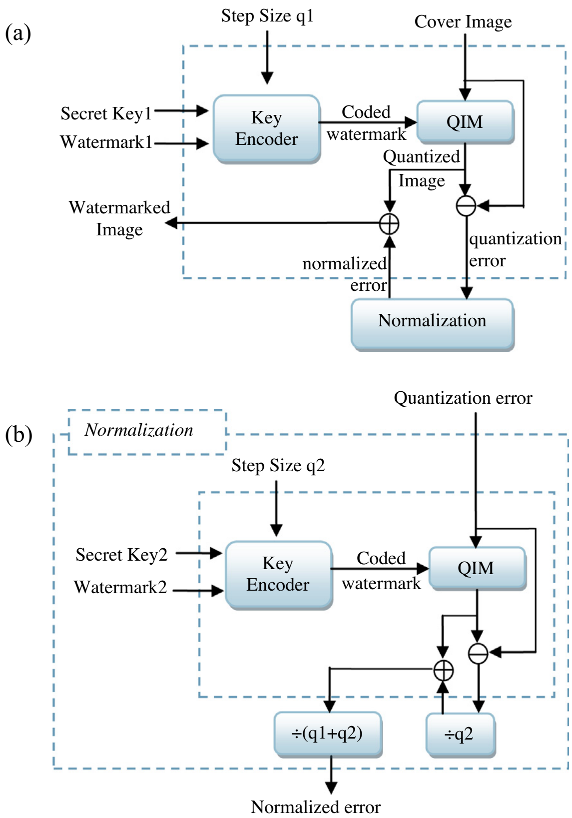

Fig. 8. (a) Basic block diagram of the embedding procedure of nested QIM based reversible watermarking technique [54]; (b) normalization process in detail.

4. Quantization based reversible watermarking

Quantization based watermarking techniques are, in general, robust. However, the reversible quantization based watermarking approaches are mostly fragile in nature. In 2007, Cheung et al. proposed a Sequential Quantization Strategy (SQS) for data embedding [17]. SQS makes the modulation of a pixel value dependent on the previous pixels. A reversible data embedding method is used with SQS to make it more suitable for the authentication purposes. Saberian et al. [88] presented a Weighted Quantization Method (WQM) approach, which can be applied in spatial as well as transform domain. In contrast to other approaches, the distortion caused by this scheme is not payload dependent. It is shown that WQM gives high embedding capacity, when applied to Point to Point Graph (PPG) transform. Lee et al. [55] proposed a vector quantization based reversible watermarking technique using histogram modification to achieve high embedding capacity.

The conventional quantization index modulation (QIM) based watermarking techniques are not reversible in general, because of the irreversible distortions caused in watermarked image due to the quantization process. However in 2011, Ko et al. [54] developed a nested QIM watermarking algorithm for medical image watermarking systems, which ensures the recovery of cover image. Embedding procedure of nested QIM based reversible watermarking technique [54] is shown in Fig. 8. Ko et al. [53] also presented a reversible watermarking technique for biomedical image using QIM and fractional discrete cosine transform (FDCT). This technique outperforms the nested QIM one [54].

5. Expansion based reversible watermarking

In 2003, Tian [95] presented a novel approach, named difference expansion (DE). It gave a new direction to the reversible watermarking methods. It achieves high embedding capacity and low computational complexity compared to the preceding techniques. Several improved DE based watermarking schemes were then proposed over the time [2,3,42,44,51,75,84,85,97]. One of the illustrious extension to the DE scheme is the prediction-error expansion (PE), proposed by Thodi et al. [92]. In this section, we discuss mainly three types of expansion based reversible watermarking techniques:

5.1. Contrast mapping based reversible watermarking

In 2007, Coltuc et al. [21] presented their work on contrast mapping based reversible watermarking. In their technique, they performed transformation of pair of pixels. The transformation is invertible for some pair of pixels, even if LSBs of transformed pairs are lost. The computational cost is low as the method is simple in nature. However, quality of the marked image suffers at both low and high payload because the variations present in the cover image are not taken into consideration during embedding. The embedding procedure for Coltuc et al.'s approach [21] is shown in Fig. 9.

To make the embedding efficient for contrast mapping based reversible watermarking, Lu et al. [66] proposed an improved version of the method presented in [21]. In 2009, Hong et al. [38] proposed another contrast mapping based approach, which is a modified version of Coltuc et al.'s approach [21]. In this technique, the cover image is first divided into a number of blocks, and then embedding is performed in blocks that are sorted according to their variances.

5.2. Prediction error based reversible watermarking

Various methods of reversible watermarking utilizing prediction error are reported in literature [15,16,19,20,26,27,45,59,61,62,68,78–80,89,90,92,93,98,99,107,113]. In 2004, Thodi et al. [92] proposed a new reversible watermarking scheme based on the correlation among the neighboring pixels for gray scale images. This correlation is modeled using a predictor, which computes the current pixel intensity.

The prediction value of a pixel p is calculated using its three neighbors as shown in Fig. 10. The predicted value $\hat{p}$ of the pixel p is obtained using median edge detector (MED) as follows:

$$\hat{p} = \begin{cases} \max(q,r) & \text{if } s \leqslant \min(q,r) \\ \min(q,r) & \text{if } s \geqslant \max(q,r) \\ q+r-s & \text{otherwise} \end{cases} \tag{1}$$

The prediction error $e = p - \hat{p}$ is expanded for the insertion of message bit b using left shift operation, and the watermarked prediction-error e_w is given by:

$$e_w = 2e + b \tag{2}$$

Since the range of pixel intensity values in a grayscale image is [0 255], embedding of watermarked prediction-error in some pixels might result in overflow/underflow. To avoid the overflow/underflow problem, only expandable pixel locations are selected for embedding. The locations that can undergo prediction-error expansion, without overflow/underflow, are called *expandable locations* [16]. Any location of the cover image that satisfies (3) is an expandable location.

$$(p+e)\begin{cases} \leqslant 254 & \text{if } e \geqslant 0 \\ \geqslant 0 & \text{if } e < 0 \end{cases} \tag{3}$$

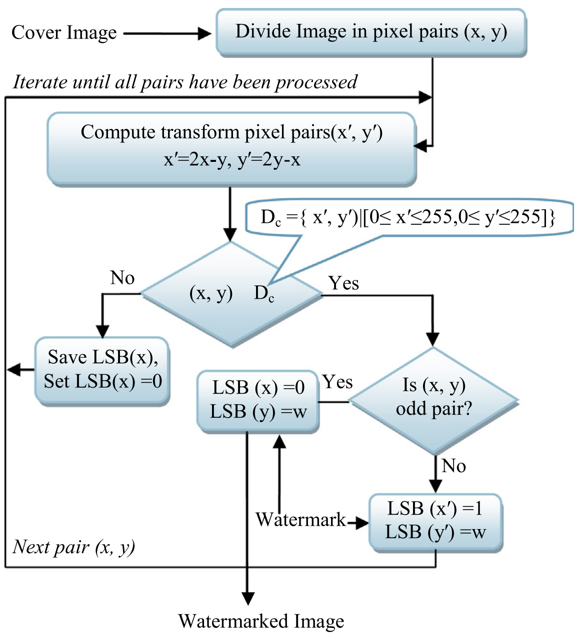

Fig. 9. Block diagram of the embedding procedure of Coltuc et al.'s [21] contrast mapping based reversible watermarking approach.

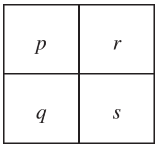

Fig. 10. Current pixel p with its three neighboring pixels q, r, and s.

Based on the predicted error e and pixel intensity p, expandable locations are identified, and a subset of expandable locations are selected by applying a threshold value T. A location map (LM) is created to indentify the selected expandable locations and is then compressed to a bitstream LM_c of length L_c for its embedding in the LSBs of watermarked image. The threshold value T depends on the size of the watermark to be embedded, and the auxiliary data comprising the LM_c and LSBs of the corresponding pixels. After embedding, the watermarked pixel intensity P is obtained using the following mathematical expression:

$$P = \tilde{p} + e_w \tag{4}$$

Here, the watermarked prediction error is added in the predicted pixel intensity. This is because alteration in predicted intensity produces less distortion compared to original pixel intensity.

At the decoding side, first the LM_c is extracted and decompressed. Then, the watermarked bits are extracted along with the recovery of the cover image using (5) and (6), respectively.

$$b = e_w - 2\left\lfloor \frac{e_w}{2} \right\rfloor \tag{5}$$

$$p = P - e - b \tag{6}$$

The embedding rate of the proposed approach attains approximately one bit per pixel (bpp). Also, multiple embedding can be applied, where a higher embedding rate is required. This technique gives better results for moderate to high embedding rates compared to DE scheme. The block diagram of Thodi et al.'s approach [92] is shown in Fig. 11, and the corresponding watermarked and difference images are shown in Fig. 12.

As the watermark is embedded only into the expandable locations, therefore, to identify those positions at detection side, mostly two approaches are used, i.e., LM [6] and histogram shifting (HS) [7]. Thodi et al. [93] improved their proposed technique [92] by introducing HS technique as a substitute to the location embedding. HS technique needs an overflow/underflow map, which takes relatively smaller space than that of the LM approach. The approach proposed by [93] reduces the distortion at low embedding rates, and moderates the capacity control problem caused by the LM embedding in [19]. The basic difference between LM and HS approaches, apart from the size of their corresponding maps, is the distortion caused in embedding process. In case of LM approach, only watermarked pixels are modified so the distortion only occurs in these pixels. Whereas, in HS approach, pixels that are not used for embedding data bits also undergo distortion because of the shifting process.

The main objectives to enhance the performance of PE based reversible techniques are: (i) minimization of the embedding distortion, (ii) maximization of the prediction accuracy, and (iii) minimization of the auxiliary data. In 2009, Tseng et al. [98] reported a simple reversible watermarking approach based on prediction-error that utilizes values of two pixels in the prediction process of each pixel. Three cases are considered in the embedding procedure. Sachnev et al. [89] reported a PE based algorithm using sorting mechanism. For estimation of the pixels, a rhombus pattern prediction is introduced. Prediction-errors are sorted based on magnitude of its local variance. In this method, pixels of the cover image are divided in two groups of alternate pixel locations as the embedding is done in two phases. In first phase, a pixel value is estimated using its four neighbors, and watermark is embedded into that pixel value but not into its prediction content. In second phase, the estimation of the remaining pixels is carried out using their four, probably, watermarked neighboring pixels. In this way, Sachnev et al.'s method [89] shows better performance compared to the techniques that employ direct raster scan in watermark embedding.

Chen et al. [15] incorporated full context for predicting every pixel intensity to get better prediction accuracy, which ensures small magnitude of prediction errors. The additive prediction error expansion (i.e., expanding the difference by addition rather than left shifting the error value) is used to embed watermark bits. The use of additive expansion makes the change in every pixel value at most by 1, which causes minor embedding distortion. In [80], a weighted linear combination of four half enclosing pixels is used for the prediction of current pixel. Through the prediction error histogram, additive error expansion is performed.

Aiming at the reduction of auxiliary data, Tudoroiu et al. [99] presented a block map based implementation using overlapping blocks. MED is used in prediction process. The flowchart of the embedding procedure for Tudoroiu et al.'s approach [99] is shown in Fig. 13.

In PE based reversible techniques, a new concept named *compensation* (a process to improve spatial correlation in neighboring pixels) is introduced by Luo et al. [68]. They subtly modified the prediction method employed in [89]. Incorporating compensation process, improves the spatial correlation in neighboring pixels and results in better prediction accuracy. It is

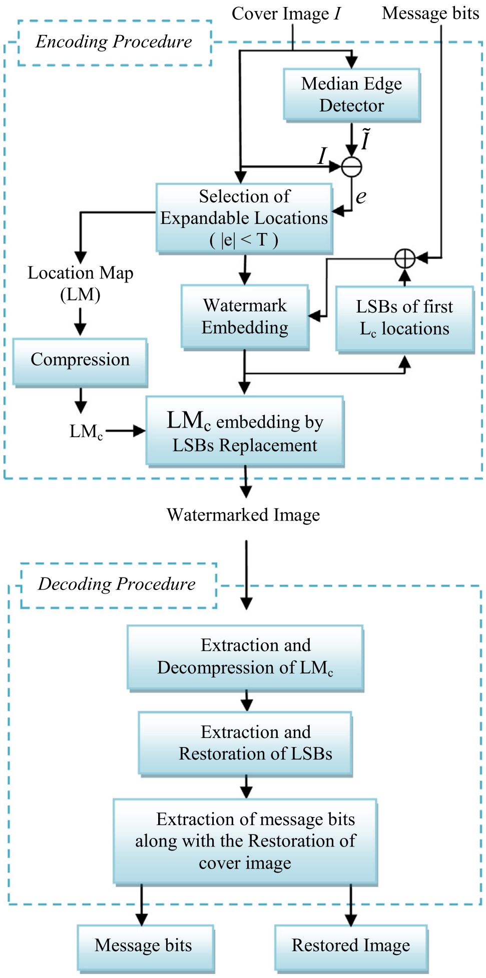

Fig. 11. Block diagram of Thodi et al.'s prediction-error expansion based reversible watermarking approach [92].

(a) (b) (c)

Fig. 12. (a) Standard Lena Image. (b) Watermarked Image using Thodi et al.'s scheme [92] with PSNR = 37.01 dB, and embedding capacity of 0.4 bpp. (c) Enhanced difference of (a) and (b).

believed that combining compensation with a more effective prediction algorithm might assure improved performance even when no watermarked pixels are interfering in the prediction process [68]. Coltuc [19] reported an improved embedding for the PE based reversible watermarking by reducing the embedding distortion into the cover image. The trick used is to divide the expanded error between the current pixel and its predefined neighborhood. A parameter delta (δ) is introduced, which is a fraction of watermarked expanded difference. δ is added or subtracted from the modified pixels and their neighborhoods. There is a trade-off between embedding distortion and prediction error (because of the embedding of delta into the neighborhood). The square error is taken into account to achieve the optimized embedding. MED, gradient-adjacent

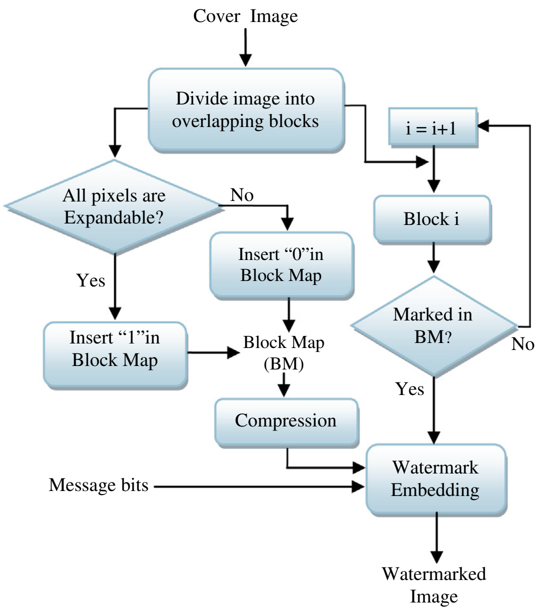

Fig. 13. Embedding procedure for the block map based implementation of Tudoroiu et al.'s [99] reversible watermarking approach.

predictor (GAP) and Simplified GAP is used to test the performance of Coltuc's technique [19]. This technique offers improvements in capacity but also increases the computational complexity compared to the simple PE based reversible watermarking.

In a recent paper [20], Coltuc introduced a simple, less computational and low distortion transform with the aim of achieving low embedding distortion by embedding not only into the current pixel, but also into its prediction context. A linear predictor; JPEG4 is used for the estimation, so the estimate of pixel p is:

$$\tilde{p} = q + r - s \tag{7}$$

where q, r, and s are the neighboring pixels of p as shown in Fig. 10.

The watermarked prediction-error e_w is defined as

$$e_w = e + b \tag{8}$$

The transformation of pixel p and its three neighboring pixels q, r, and s (that are used as prediction context) after the embedding process to P, Q, R and S is carried out as follows:

$$P = p + e_w - 3\delta, Q = q - \delta, R = r - \delta, S = s + \delta \tag{9}$$

The square error caused by embedding is

$$E^2 = (P - p)^2 + (Q - q)^2 + (R - r)^2 + (S - s)^2 = 12\delta^2 - 6e_w\delta + e_w^2 \tag{10}$$

The minimization of square error (E^2) is carried out for computing $\delta = e_w/4$. The value of δ is then divided into four components i.e., δ_p, δ_q, δ_r, and δ_s such that the sum of these components equals to e_w. Thus, (9) is modified to (11) as:

$$P = p + \delta_p, Q = q - \delta_q, R = r - \delta_r, S = s + \delta_s \tag{11}$$

The transform is obtained using an optimized embedding procedure and simple linear prediction. Also, it is shown that PE schemes with optimized embedding are equivalent to that of Tian's DE transform based approach [95].

In a recent paper, Li et al. [61] reported a prediction error based reversible watermarking scheme, which aims at achieving high imperceptibility in term of peak-signal-to-noise-ratio (PSNR). A new prediction strategy called pixel value ordering (PVO) is introduced. First, image is divided into blocks of size n x n. Then, PVO is applied on each block and maximum and minimum prediction error is calculated. Only maximum and minimum values of each block are modified during embedding. Watermark bit is inserted when prediction error is either '1' or '-1'. At most two bits can be embedded into each block. However, this scheme has rather limited embedding capacity, e.g. only 32,000 bits can be embedded into Lena Image of size 512×512 for the block size of 2×2. Coatrieux et al. [18] reported a technique in which dynamic prediction error histogram shifting is used for embedding. The cover image pixels are classified into two regions i.e. pixel histogram shifting (PHS) region and dynamic prediction-error histogram shifting (DPEHS) region. The information bits to-be-embedded are divided into two sets i.e. m1 and m2. Fig. 14 shows the block diagram of the embedding procedure for Coatrieux et al.'s approach [18].

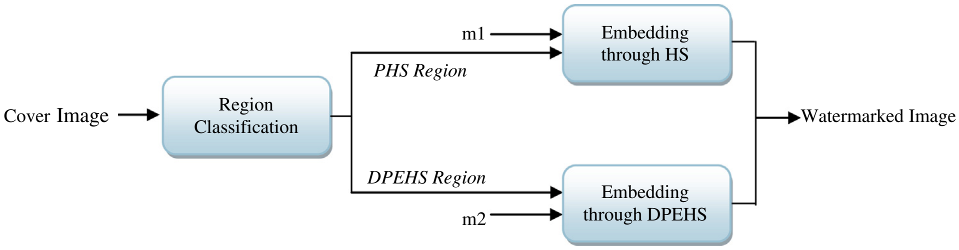

Fig. 14. Embedding procedure of Coatrieux et al.'s [18] prediction-error based reversible watermarking approach.

Dragoi et al. [24] reported an improvement in Sachnev et al.'s method [89] by performing adaptive prediction of the pixels that do not belong to smooth regions. Coltuc et al. [22] presented a prediction error expansion based high capacity multi-bit embedding algorithm, and compared its performance with multi-level embedding algorithm. Wu et al. [106] proposed a hybrid approach in which embedding is carried out using HS of prediction errors that are obtained by applying Sachnev et al.'s method [89]. Zhou et al. [115] proposed a method for optimization of parameters that control the capacity of prediction error expansion algorithms e.g., the threshold T.

5.3. Interpolation based reversible watermarking

Image interpolation is a process of estimating the missing pixels. Consider an image of size $2M \times 2N$, which is down-sampled to get a low resolution (LR) image of size $M \times N$ [112]. The pixels present in the low resolution image are called sample pixels. Using these sample pixels, missing pixels of high resolution image i.e., non-sample pixels, are interpolated to construct the interpolated image of size $2M \times 2N$. The difference between the interpolated pixel value and the original pixel value is called interpolation error. Several reversible watermarking techniques based on interpolation error are proposed [1,40,67,72]. Interpolation error expansion differs from rest of the DE schemes in two ways. First, it employs interpolation error for data embedding instead of adjacent pixels difference or prediction error. Secondly, it expands the error by addition rather than bit shifting. It also exploits the correlation between neighboring pixels more extensively than PE schemes.

Luo et al. [67] reported a reversible watermarking method using interpolation technique. The watermark bits are first embedded in the non-sample pixels until no non-sample pixel is left. Then, the rest of the watermark bits are inserted into the sample pixels, which are interpolated using neighboring watermarked pixels. This scheme provides less embedding

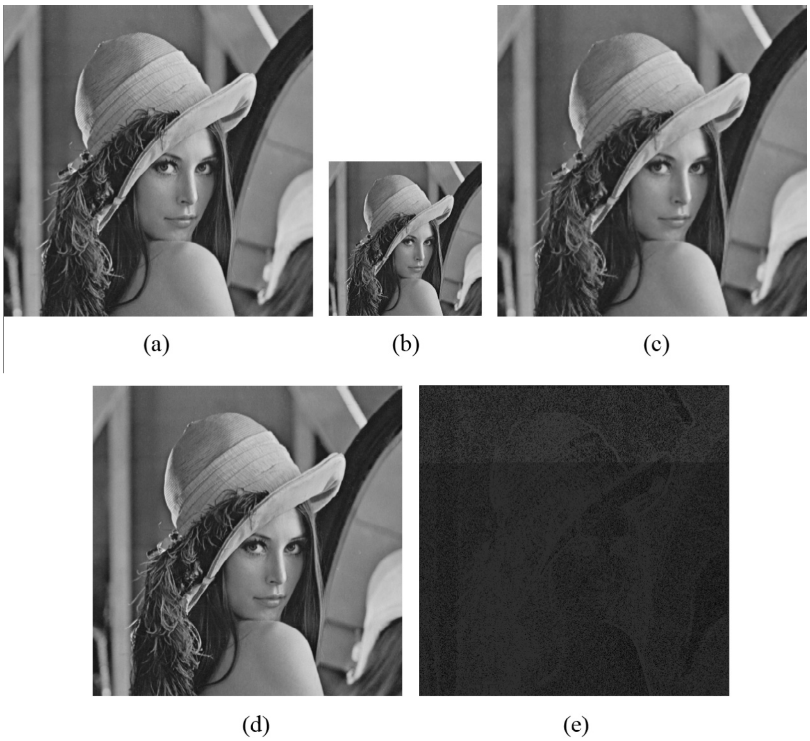

Fig. 15. (a) Cover Image. (b) LR Image. (c) Interpolated Image. (d) Watermarked Image using Luo et al.'s [67] scheme with PSNR = 39.01 dB, and embedding capacity of 0.75 bpp. (e) Enhanced difference of (a) and (d).

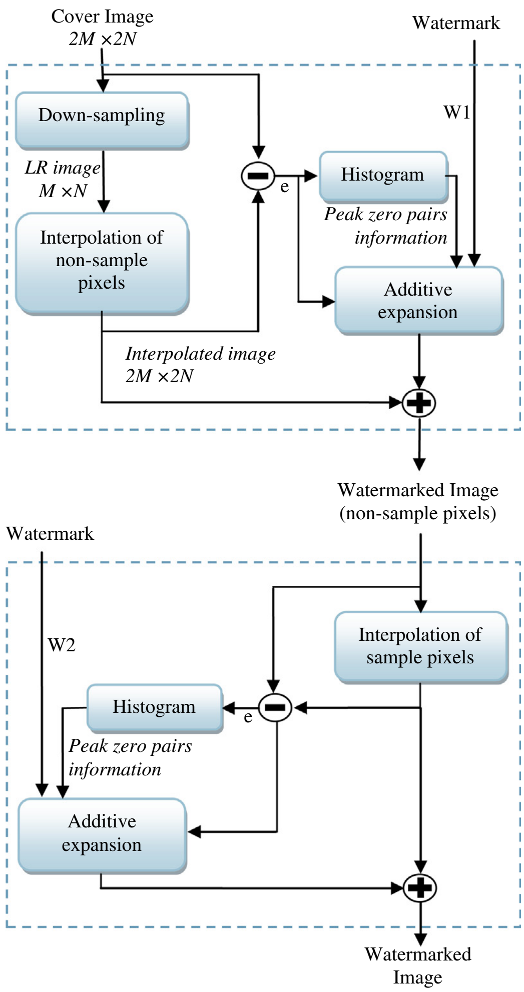

Fig. 16. Embedding procedure of Luo et al.'s [67] interpolation error based reversible watermarking approach.

distortion and low computational cost, which result in better image quality and efficient algorithm, respectively. But the pixels having value 0 or 255 are not considered for embedding in order to prevent overflow/underflow, which makes the boundary map large in size and embedding capacity to suffer. So, it is not suitable for watermarking the medical images. The cover, LR, interpolated, and watermarked images are shown in Fig. 15, whereas, Fig. 16 shows the basic block diagram of the embedding procedure of the watermark (W1 in non-sample pixels, and W2 in non-sample pixels) for Luo et al.'s technique [67].

A modification to Luo et al.'s method [67] is presented by Abadi et al. [1]. By using histogram shifting method, the pixels of the cover image with values '0' and '255' are shifted to '1' and '254' respectively, to prevent any overflow/underflow during embedding process. This approach achieves high embedding capacity compared to [67] as boundary pixels are utilized in data embedding. Naheed et al. [72] also reported an improved version of Lou et al.'s [50] scheme by utilizing particle swarm optimization in the estimation of missing pixels. For Lena image of size 512x512 at PSNR of 48.82 dB, an embedding capacity of 0.27 bpp is achieved by Luo et al. [67], at 48.78 dB, 0.28 bpp is reported in [1], and at 48.85 dB, 0.28 bpp is reported in [72]. However, Abadi et al. [1] and Naheed et al. [72] only reported the embedding capacity at a constant PSNR for comparison.

6. Comparison and discussion

Comparison of different existing reversible watermarking techniques is presented in Table 1. While, Table 2 shows the comparison of prediction error based reversible watermarking techniques. Overall, from these tables it can be observed that most of the reversible watermarking techniques are fragile, and thus are useful in content authentication applications.

6.1. Comparison of different reversible watermarking techniques

It can be seen from Table 1 that these techniques do not need cover image related information at detection side except for methods reported by Ni et al. [77] and Gao et al. [32]. Vleeschouwer et al. [102] scheme is semi fragile as it shows some robustness against JPEG compression. Though, it shows better visual quality of marked image than [9] and [103], it still suffers from some salt and pepper noise because of modulo addition 256. Celik et al. [9] extended the work of Fridrich et al. [31]. Histogram based watermarking techniques reduce the size of auxiliary information that needs to be embedded in the cover image along with the watermark. Thus, more space is available consequently, increasing the embedding capacity. Celik et al.'s [9] approach can achieve considerable higher embedding capacity than Fridrich et al.'s method [31] at comparable PSNR. Fridrich et al.'s [16] approach has comparatively less embedding capacity due to lower compression ratio. However, Celik et al. [9] has complex implementation compared to Fridrich et al. [31]. Xuan et al.'s [108] method outperforms Tian's method [95], and achieves higher PSNR with improved capacity because Xuan et al. [108] used a companding function. Embedding is carried out in high frequency subbands, which cause less distortion. Arsalan et al.'s technique [6] shows improved results compared to Xuan et al.'s method [108], mainly because Arsalan et al.'s technique [6] finds an optimal threshold for each block using genetic algorithm. However, optimization of threshold takes time, making Arsalan et al.'s technique [6] computationally expensive.

First QIM based reversible watermarking algorithm is developed by Ko et al. [54]. However, it is not robust. The advantage of contrast mapping based techniques over other reversible watermarking approaches is its robustness. Coltuc et al.'s [21] approach shows some robustness against cropping. It has simple implementation and does not need additional data compression. In order to achieve higher embedding capacity, Tian's [95] approach exploits the inter-pixel redundancies present in the cover image. Luo et al. [67] utilize the basic concept of difference expansion and introduces additive interpolation-error expansion. This approach does not perform embedding in pixels having values '0' or '255' resulting in low embedding capacity. In case of multilayer embedding, it shows low distortion and higher embedding capacity compared to Kim et al.'s [29] approach.

6.2. Comparison of prediction error based reversible watermarking techniques

Table 2 shows the comparison of different prediction error based reversible watermarking techniques. All the techniques listed in Table 2 are fragile and blind. In prediction error expansion based reversible watermarking, embedding distortion introduced in the image directly depends on the prediction error. Therefore, to reduce the magnitude of prediction error, different types of predictors and prediction context are used. Third column of Table 2 listed few predictors and number of pixels used as prediction context.

Thodi et al. [92] reported the first prediction-error based reversible technique. It outperforms Tian's DE method [95] at high embedding capacity, as it embeds the watermark bits in the prediction error rather than in the difference of two consecutive pixels. The predicted error will be less as compared to difference between the consecutive pixels resulting in

Table 1
Comparison of different reversible watermarking techniques.

Technique	Type	Blind/ semi-blind	Remarks
Compression based reversible watermarking			
Celik et al. [9]	Fragile	Blind	Outperforms Fridrich et al.'s [31] scheme Embedding capacity depends on quantization levels
Xuan et al. [108]	Fragile	Blind	Improved capacity vs. PSNR tradeoff. High Auxiliary data
Arsalan et al. [6]	Fragile	Blind	Improved capacity vs. PSNR tradeoff. High training time
Histogram based reversible watermarking techniques			
Vleeschouwer et al. [103]	Semi-Fragile	Blind	Introduces salt pepper noise
Vleeschouwer et al. [102]	Semi-fragile	Blind	Introduces salt pepper noise
Ni et al. [77]	Robust to JPEG compression	Semi-Blind	Not completely reversible
Gao et al. [32]	Robust to JPEG compression	Semi-Blind	Requires high auxiliary data. Offers relatively low capacity
Quantization based reversible watermarking			
Ko et al. [54]	Fragile	Blind	Uses nested QIM to achieve reversibility. The watermarked image suffers from block effect
Ko et al. [53]	Fragile	Blind	Uses QIM at first stage and FDCT at second stage. No block effect in the watermarked image Its performance is better than nested QIM [54]
Contrast mapping based reversible watermarking			
Coltuc et al. [21]	Robust to cropping	Blind	Simple in implementation. Does not need additional data compression
Lu et al. [66]	Robust to cropping	Blind	Shows better PSNR compared to [21]
Expansion based reversible watermarking			
Tian [95]	Fragile	Blind	Uses inter-pixel redundancy. Higher embedding capacity and PSNR than [31] and [9]
Luo et al. [67]	Fragile	Blind	Offers better imperceptibility and higher capacity compared to [46]. Boundary pixels are not utilized in embedding
Abadi et al. [1]	Fragile	Blind	Improves Luo et al.'s [67] method by utilizing boundary pixels in embedding

Table 2
Comparison of prediction based reversible watermarking techniques.

Technique	Expansion type	Predictor type (No. of Pixels used in prediction)	Remarks
Thodi et al. [92]	Prediction Error	MED(3)	Outperforms Tian's DE method at high embedding rates Achieves approximately 1 bpp embedding rate with single embedding
Thodi et al. [93]	Prediction Error	MED(3)	Introduces HS method to replace large LM with much smaller auxiliary information Maximum embedding capacity is around 1 bpp in a single pass
Sachnev et al. [89]	Prediction Error	Rhombus Pattern Prediction(4)	Two stage embedding method makes each pixel available for embedding in an ideal case, thus allowing the embedding capacity to reach 1 bpp It offers better performance than that of [93]
Chen et al. [15]	Additive Prediction Error	Full Context Prediction(8)	Utilizes full context for more accurate estimation and small prediction-error It causes less embedding distortion It shows high embedding capacity compared to [93] at constant PSNR
Ou et al. [80]	Additive Prediction Error	Weighted Average(4)	In case of Lena image, this method performs better than [89] on average about 1 dB higher, when the embedding rate is above 0.2 bpp In case of Airplane image, it provides about 3 dB high PSNR on average
Tudoroiu et al. [99]	Prediction Error	MED(3)	Uses block map to reduce the size of LM For block size 8x8, it outperforms the basic LM approach and provides comparable results with the HS approach [93]
Luo et al. [68]	Prediction Error	Compensated Average(4)	Uses compensation concept during data embedding It can improve the PSNR obtained in [89] to 0.5 dB or above.Wrong judgment of modification direction with large translation quantity can cost too much
Coltuc [19]	Prediction Error	MED(3), GAP(7), SGAP(4)	It analyzes the trade-off between optimization of embedding and improvement in performance of the proposed scheme Considerable performance improvement is shown for the case of MED and SGAP predictors
Coltuc [20] (2012)	Prediction Error	JPEG4(4)	Very simple low distortion transform Suitable for application that requires low embedding capacity like captioning, labeling etc Outperforms Tian's DE transform
Li et al. [61]	Prediction Error	PVO(4)	Provides high fidelity at rather low embedding rate Like [20], it is useful in applications requiring low embedding capacity

improved performance. It can achieve a capacity greater than 0.5 bpp. It requires user defined threshold value where, higher value will downgrade the image quality and vice versa. Thodi et al.'s [93] method further improves the embedding capacity of Tian [95] and Thodi et al.'s [92] methods by introducing HS method. Consequently, size of auxiliary information to be embedded is decreased. Sachnev et al. [89] incorporated sorting for improvement in the performance of prediction error expansion. Embedding is carried out in two phases. It performs better compared to that of Thodi et al.'s approach [93].

Sachnev et al. [89] employed two-stage watermarking by dividing the image into two halves, and they reported superior results on Lena image of size 512×512, so far. Chen et al. [15] used full context prediction to fully exploit correlation between pixels of the cover image. Also, embedding distortion is low because additive expansion used causes pixel change at most by 1. They provided results comparison with Thodi et al.'s [93] at a constant PSNR, which show improvement in embedding capacity. Tudoroiu et al. [99] implemented block map based prediction error expansion to reduce the amount of auxiliary data. This block map based implementation outperforms Thodi et al.'s approach [92], and shows comparable results to Thodi et al. [93]. Luo et al. [68] introduced the concept of compensation in prediction error expansion that improves prediction accuracy by utilizing the spatial redundancy in neighboring pixels effectively. Coltuc [19] aimed at improved embedding by minimizing the embedding distortions. Coltuc incorporated different predictor for estimation process and shows improvement in performance compared to Thodi et al.'s approach [92]. However, computational complexity of Coltuc's approach [19] is increased compared to the basic PE approach. In his recent paper [20], Coltuc used a simple linear predictor JPEG4 and outperformed Tian's DE method [95].

The reversible watermarking approach presented in [20] is more suitable in applications that require low embedding capacity. Li et al.'s [61] scheme achieves higher PSNR compared to [89] and [67] at embedding capacity of 10 K bits. Fig. 17 shows PSNR versus capacity curve for different reversible watermarking techniques.

7. Experimental evaluation

In this section, experimental evaluation of some of the reversible watermarking techniques is presented. In general, evaluation metrics for conventional digital watermarking systems can be robustness, imperceptibility, embedding capacity, computational time, and security. Some benchmarking tools exist for testing the performance of robust watermark techniques i.e., StirMark [87] and CheckMark [86], etc. benchmarks. However, there is lack of benchmarking tools for the evaluation of reversible watermarking techniques. For evaluation of reversible watermarking techniques, performance metrics such as imperceptibility (in terms of PSNR, SSIM index, etc.), embedding capacity (in bits per pixel i.e., bpp), and temporal cost (in seconds) are usually used.

In this work, we used two datasets for conducting experiments on several reversible watermarking techniques. First dataset consists of 300 images (jpeg format) of size 512 × 512 and the second dataset, which is a large dataset, comprises of 1500 images of size 256 × 256 [116–118].

7.1. Performance on dataset of 300 images

First, imperceptibility in terms of PSNR is plotted against number of images at a constant capacity of 1 K bits. PSNR is averaged over 10 images as shown in Fig. 18. Results of HS implementation of Coltuc's method [20] in single pass are shown. The maximum embedding capacity for this method in single pass is 0.25 bpp. In embedding algorithm of Li et al.'s scheme [61], only maximum of the block is utilized.

Block size is kept 2 × 2 for experimentation. This way, the maximum embedding capacity of Li et al.'s approach [61] can also reach up to 0.25 bpp. It is observed that the results of Coltuc's method show more variations in PSNR values compared to Li et al.'s [61] or Gao et al.'s [32] method. Coltuc's method [20] utilizes prediction error to embed watermark bits, and the magnitude of prediction error depends on the content. Therefore, variations in PSNR plot reveal the dependence of Coltuc's embedding method on the characteristics of digital content of the image. Gao et al.'s plot against 300 images shows only slight variations in PSNR values, which implies that Gao et al.'s scheme [32] is independent of image content. Results of high embedding capacity techniques such as Thodi et al.'s [93], Luo et al.'s [67], and Sachnev et al.'s [89] are also plotted at 1 K bits. PSNR variations in Thodi et al.'s and Sachnev methods are identical; however, Sachnev et al.'s scheme [89] outperforms Thodi et al.'s method [93]. It is observed from Fig. 18 that Luo et al.'s technique [67] shows overall superior results at 1 K bits capacity. This is due to the fact that Luo et al. [67] employed additive embedding which causes low distortion compared to expansion by two. Structural similarity index measure (SSIM) index is also plotted against number of images at embedding capacity of 1 K bits (Fig. 19). In contrast to PSNR, SSIM index is quality assessment based on the assumption that human visual perception is highly adapted for extracting structural information from a scene. It can be thought of as a similarity measure for comparing any two images [105], and its value ranges from 0 to 1. Temporal comparison at embedding capacity of 1 K bits is provided in Supplementary Table 1. Embedding time is computed by averaging over 10 images. It is observed

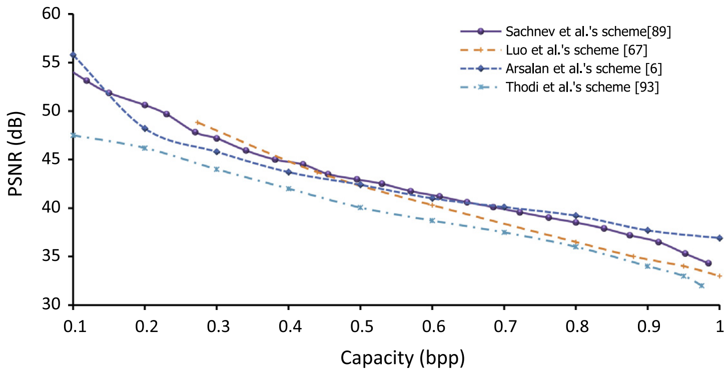

Fig. 17. PSNR vs. Capacity curve for different reversible watermarking techniques using Lena image.

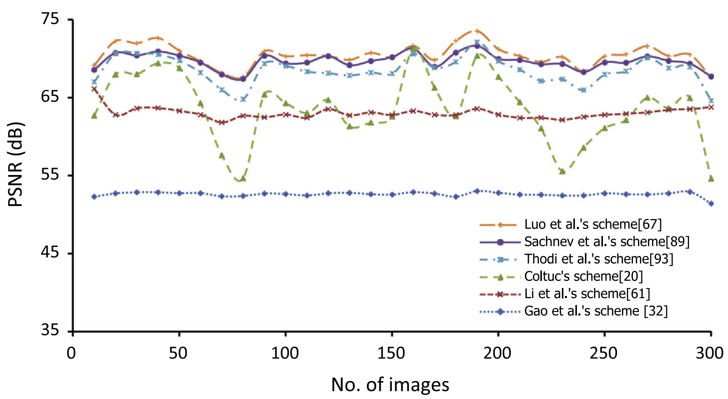

Fig. 18. Average PSNR of 10 images versus number of images at a constant embedding capacity of 1 K bits.

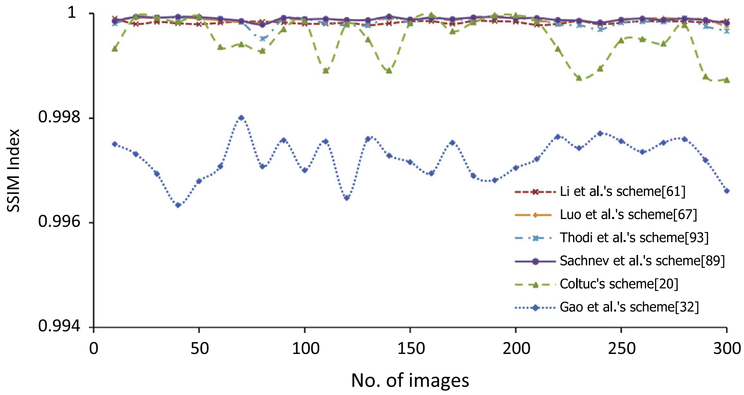

Fig. 19. SSIM index averaged over 10 images versus number of images at a constant embedding capacity of 1 K bits.

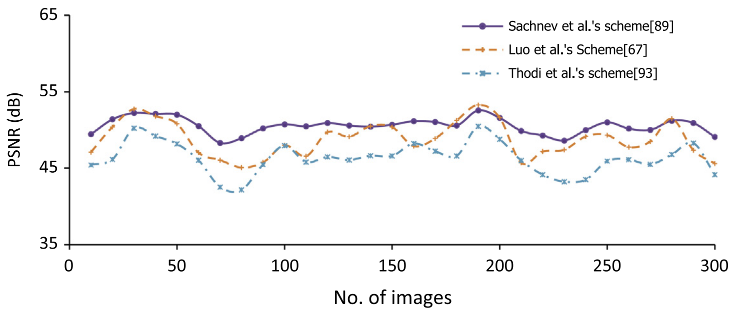

Fig. 20. Average PSNR of 10 images versus number of images at a constant embedding capacity of 0.25 bpp.

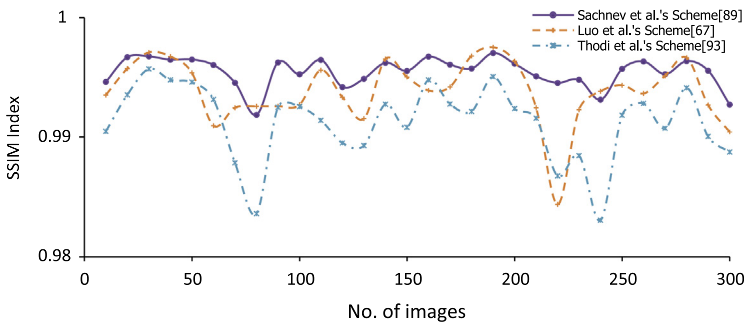

Fig. 21. SSIM index averaged over 10 images versus number of images at a constant embedding capacity of 0.25 bpp.

from Supplementary Table 1 that Thodi et al.'s and Sachnev et al.'s methods are taking shortest average time, compared to rest of the techniques. On the other hand, Gao et al.'s technique is taking longest average time per image for embedding 1 K bits, mainly due to the use of BCH coding.

Another experiment is carried out on the same dataset of 300 images; however, the embedding capacity is kept at 0.25 bpp. Results of Thodi et al. [93], Luo et al. [67] and Sachnev et al. [89] 's algorithms in terms of PSNR averaged over 10 images are plotted against number of images. Fig. 20 shows the variations in Thodi et al. [93], Sachnev et al. [89] and Luo et al. [67]'s embedding methods. As mentioned earlier, these variations show the dependence of embedding algorithm on the test image. It is also observed that Sachnev et al.'s technique shows overall superior results at embedding capacity of 0.25 bpp. Similarly, SSIM index is also plotted against number of images at embedding capacity of 0.25 bpp. Similarly, SSIM index is also plotted against number of images at embedding capacity of 0.25 bpp (Fig. 21). Temporal comparison of these techniques is also provided in Supplementary Table 1 at embedding capacity of 0.25 bpp. Sachnev et al.'s technique [89] is taking shortest average time at embedding capacity of 0.25 bpp. Temporal comparison for these techniques is also shown in Fig. 22. It is observed that Thodi et al.'s scheme [93] is taking lowest time for embedding capacity of 1 K bits. These simulations are run on Dell Optiplex 990 machine, with 3.40 GHz processor and 8 GB of RAM.

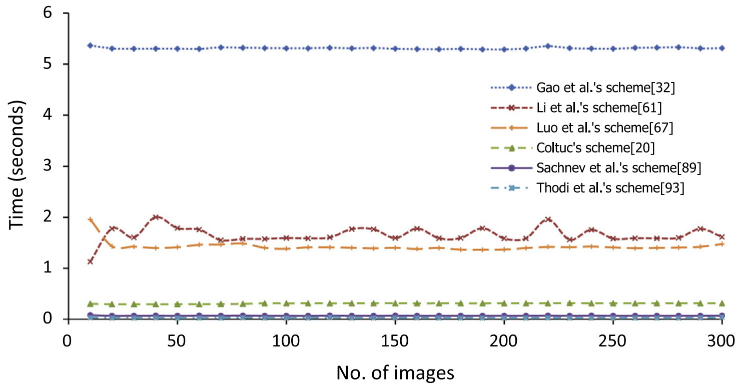

Fig. 22. Embedding time averaged over 10 images versus number of images at a constant embedding capacity of 1 K bits.

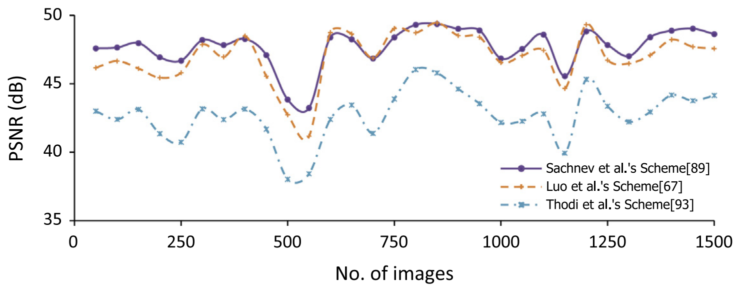

Fig. 23. PSNR averaged over 50 images versus number of images at a constant embedding capacity of 10 K bits.

7.2. Performance on dataset of 1500 images

Experiments are also performed on a database of 1500 images of size 256×256 for the embedding capacity of 10 K bits. PSNR and SSIM index plots are shown in Figs. 23 and 24. In PSNR plot, Luo et al.'s and Sachnev et al.'stechniques are somewhat comparable; whereas, in SSIM plot Sachnev et al.'s scheme [89] clearly outperforms Luo et al.'s approach [67]. Dell Optiplex 990 machine, with 3.40 GHz processor and 8 GB of RAM is used in testing.

7.3. Suitability of reversible watermarking techniques for real-time large image databases

In general, the watermarking techniques are content dependent. It can be verified from the variations in PSNR and SSIM index plots as shown in Figs. 23 and 24. These experiments are performed on a large image database that contains diverse images. One of the major issues in using real-time large image databases for watermarking is the embedding effectiveness. Embedding effectiveness of a watermarking system is the probability that the output of the embedder will be watermarked. While 100% effectiveness is always desirable, this aim often comes at the cost of some other characteristics e.g., imperceptibility [23].

Three high capacity reversible watermarking techniques are tested on the database of 1500 images for embedding of 10 K bits per image. Thodi et al.'s technique [93] resulted in 92% embedding effectiveness, whereas Luo et al.'s and Sachnev et al.'s methods showed 91.33% and 83.33% effectiveness, respectively. Embedding effectiveness can be significantly improved by optimizing the parameters values involved in embedding process for each image. In other words, making the watermarking techniques adaptive will improve the embedding effectiveness. For instance, Thodi et al.'s scheme is tested at a constant threshold value T for all images and resulted in 92% of effectiveness. Setting the higher threshold than T would result in effectiveness greater than 92%; however, it would lower the imperceptibility measure i.e., PSNR curve. Sachnev et al.'s method [89] is also tested at constant thresholds T_n and T_P for all images in the database. Similarly, embedding effectiveness of Sachnev et al.'s method can be improved by increasing the embedding interval thresholds. For Luo et al.'s technique [67], optimization of weights involved in interpolation process may results in improved embedding effectiveness. Consequently, we anticipate that a better way of increasing the embedding effectiveness is to use adaptive techniques for embedding.

Apart from embedding effectiveness, embedding and extraction time is major issue in real-time big databases. Luo et al.'s technique lags behind Thodi et al.'s and Sachnev et al.'s methods with respect to embedding time as shown in Fig 25. Some interesting works related to watermarking of bi-tonal images are specifically designed for large databases [100,101].

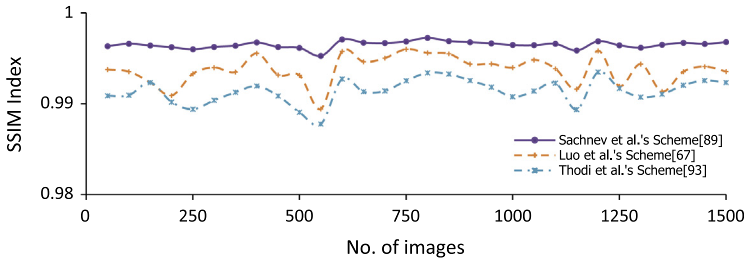

Fig. 24. SSIM index averaged over 50 images versus number of images at a constant embedding capacity of 10 K bits.

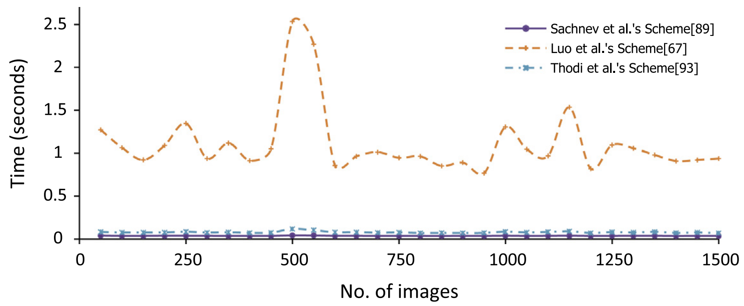

Fig. 25. Embedding time averaged over 50 images versus number of images at a constant embedding capacity of 10 K bits.

8. Conclusions

In this survey, we have categorized reversible watermarking into four major categories; (1) Compression based, (2) Histogram modification based, (3) Quantization based, and (4) Expansion based watermarking. From literature, it is very difficult to draw a sharp boundary between these categories. Many researchers have even developed hybrid approaches by combining different techniques.

The performance of several relevant reversible watermarking approaches is analyzed through capacity, imperceptibility, and computational cost. Our analysis is that expansion based reversible watermarking approaches are effective, and easy to implement compared to some other reversible watermarking techniques.

Some of our findings related to reversible watermarking techniques are:

(a) Compression based approaches helps in increasing the embedding capacity.
(b) Histogram based techniques reduce the size of auxiliary data and are either semi-fragile or robust.
(c) Contrast mapping based watermarking (which is a type of difference expansion) techniques do not need additional data and can be robust to some extent.
(d) Prediction-error expansion based reversible watermarking is a newly emerging and prospective approach. Additionally, it is computationally less intensive.
(e) It is observed that most of the prediction-error expansion based schemes are aiming at maximizing the prediction accuracy, lowering the embedding distortion (which in turns improves the imperceptibility). While, others are targeted towards achieving high embedding capacity.

We have observed that almost all of the reversible watermarking approaches, one way or the other, create space for bit embedding by effectively performing less HVS (human visual system)-observable manipulations in the contrast of an image. This happens directly in case of contrast based, while indirectly in case of histogram processing, Compression, etc. based reversible watermarking approaches. However, the effective approach is the one that can create more space at low cost of HVS-observable distortions.

8.1. Future directions

From the works that have been discussed here, it is established that most of the reversible watermarking approaches are fragile. Moreover, this fragility is making them suitable for content authentication based applications. In general, most of the reversible watermarking techniques are not capable of identifying any tampered locations, if the watermarked work undergoes any kind of modifications. However, Malik et at. [70] and Naskar et al. [73] have recently reported a tamper localization technique for reversible watermarking. We believe work in this direction has a good scope in future.

Additionally, the field of reversible watermarking lacks in benchmarking tools for the evaluation of techniques. Development of the benchmarking tools is necessary to make reversible watermarking techniques easy to be compared and reliable. Similarly, so far to the best of our knowledge, in literature, security of the reversible watermarking techniques is not discussed and analyzed in detail. Therefore, a possible future direction is to perform security analysis of the reversible watermarking approaches. In summary, till to date, quite interesting works have been reported by different researchers in the field of reversible watermarking but, there still exist room for improvement as regards performing a tradeoff between watermark capacity and imperceptibility, tamper localization, security, and benchmarking.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ins.2014.03.118.

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