Utilizing Least Significant Bit-Planes of RONI Pixels for Medical Image Watermarking

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Abstract—We propose a computationally efficient image border pixel based watermark embedding scheme for medical images. We considered the border pixels of a medical image as RONI (region of non-interest), since those pixels have no or little interest to doctors and medical professionals irrespective of the image modalities. Although RONI is used for embedding, our proposed scheme still keeps distortion at a minimum level in the embedding region using the optimum number of least significant bit-planes for the border pixels. All these not only ensure that a watermarked image is safe for diagnosis, but also help minimize the legal and ethical concerns of altering all pixels of medical images in any manner (e.g., reversible or irreversible). The proposed scheme avoids the need for RONI segmentation, which incurs capacity and computational overheads. The performance of the proposed scheme has been compared with a relevant scheme in terms of embedding capacity, image perceptual quality (measured by SSIM and PSNR), and computational efficiency. Our experimental results show that the proposed scheme is computationally efficient, offers an image-content-independent embedding capacity, and maintains a good image quality of RONI while keeping all other pixels in the image untouched.

I. INTRODUCTION

Digital watermarking is a promising data hiding technique for medical image applications. It has three major components: watermark generation, watermark embedding, and watermark detection [1]. Watermark generation generates the watermark(s) depending on the watermarking objective (e.g., authentication, integrity verification, annotation). Watermark embedding—the data-hiding component—considers where and how to embed the watermark (with any side information, which altogether constitute a payload) satisfying various requirements of the cover objects (here, medical images), as shown in Fig. 1 Watermark detection, on the other hand, is responsible for making a reliable and objective decision with minimum error probabilities (e.g., false negative/positive rates) and computation time. Although all these three components are important, we limit our focus in this paper to watermark embedding to mainly address the legal and ethical concerns, for a medical image watermarking framework.

A medical image application framework of digital watermarking aims at achieving different security properties such as authentication and/or integrity verification of the medical images, confidentiality of meta-data (e.g., EPR—electronic patient record) etc. These security properties can be readily achieved by using the standard cryptographic techniques. However, due to (temporary) loss of any spatial information of medical images, direct use of those techniques may obliterate any semantic understanding of the images. Digital watermarking can help overcome this obliteration problem and borrow the security properties of the cryptographic techniques by embedding the watermark imperceptibly and efficiently. Here, watermark generation requires a suitable cryptographic technique to be deployed according to the watermarking objectives, which is beyond the scope of this paper.

However, since any watermark embedding incurs an inevitable distortion, digital watermarking has to address a few conflicting requirements for medical images to ensure (i) continuous protection of the image, and (ii) acceptable levels of embedding distortion in the image. Continuous protection of a medical image broadly means the protection of the image for all entities (e.g., systems and users) that the image may pass through during its lifetime, which requires the watermark to remain embedded continuously. Acceptable embedding distortion, on the other hand, ensures that the watermarked images can be accepted by the medical professionals for any medical or clinical uses. Here, if the incurred embedding distortion is removed, security protection discontinues; if not, legal and ethical concerns arise.

The legal and ethical concerns about altering image pixels is reducing the practicability of digital watermarking for medical images [2]. Medical professionals remain sceptical about allowing possible alteration of all the pixels (in a medical image) irrespective of the techniques (e.g., reversible, irreversible, etc.) and the levels of incurred distortion of watermark embedding [2]. This scepticism motivates researchers to consider the RONI (region of non-interest) in medical images that are of no or little interest to doctors and medical professionals. However, finding a suitable RONI segmentation technique, in general for all modality medical images, remains as a fundamental problem. (There are many modalities of medical images: CT–Computed Tomography, MR Magnetic Resonance, X-ray, DSA–Digital Subtraction Angiography, RF–Radio Fluoroscopy, US—Ultrasound, MG–Mammography, to name a few.) Because, different medical images have different perceptual content and random location of ROI (region of interest, the complementary region of RONI in medical images that presents the anatomical objects or important features for diagnostic purposes).

In order to (i) overcome ROI/RONI segmentation problem, (ii) minimize the legal and ethical concerns, and (iii) facilitate the continuous protection of medical images, we study the border pixels of medical images and propose an irreversible and spatial domain (border pixel based) embedding scheme. We start with finding a set of suitable least significant bit-
planes of the border pixels for watermark embedding, which leads us to maintaining a good (perceptual) quality in the embedding region, keeping the other pixels in the image untouched. Our proposed scheme further attempts to achieve an image-(perceptual)-content-independent capacity with a low computational complexity.

This paper is organized as follows. Section II briefly reviews the relevant literature. Section III introduces the proposed watermark embedding scheme, and its features, practicability and implementation. Experimental results and performance analysis are presented in Section IV. Finally, Section V presents conclusions and future works.

II. RELATED WORKS

This section briefly reviews some relevant digital watermarking schemes, particularly those addressing the ROI (or RONI) segmentation as well as the embedding distortion minimization problems.

ROI segmentation is, more or less, assumed to be carried out properly by the intervention of doctors, radiologists or medical experts [3]–[8]. This is not efficient for any institute or health care system, where the number of medical images produced every day is potentially very high. Since one segmentation technique is not equally suitable for different modality images, different techniques were also introduced for specific modalities. For example, ROI is defined by using—rectangles for MR-brain image [9], polygons for CT, MR, and US [10], logical ellipses for CT, US, X-ray, and MR images [11], morphology operations for MR images [12], and K-means segmentation methods for MR images [13]. Most of the medical image watermarking schemes that considered ROI or RONI, suffer from the computational overhead of segmentation. In addition, a significant portion of the capacity is also eaten up by the ROI pointers as a side information to re-locate the exact ROI later at the detector. In summary, the main ROI segmentation problems include (i) computational overhead, (ii) side information overhead, and (iii) limited practicability (i.e., not suitable for all modality medical images).

Moreover, embedding distortion in the ROIs has been addressed in different ways in the literature. In order to ensure a minimum level of distortion in ROIs, a perceptual-content-adaptive embedding approach was considered [14]. In compliance with strict medical image requirements (of completely preserving anatomical objects in the ROIs), however, two techniques have been commonly used: (i) lossless compression of ROIs [3], [6] and (ii) reversible embedding [10], [12], [15]–[21]. Reversible embedding techniques are advantageous over ROI compression based techniques, mainly due to having lower embedding distortion without any computational overheads of ROI segmentation and compression.

Reversible embedding introduces an invertible distortion in a watermarked image that can be restored to the original when required. Many reversible watermarking schemes have been reported since the Barton patent [15] in 1997. However, the difference expansion (DE) [17] and histogram shifting (HS) [20] based reversible watermarking and their recent developments [10], [12], [18], [21] have attracted increasing interest in medical image applications.

Coatrieux et al. [12] proposed a RONI based reversible watermarking scheme for MR images that offers a continuous reliability protection of the image. However, morphology operations based RONI segmentation of that scheme is not suitable for all modalities of medical images. Lee et al. [18] introduced a reversible watermarking scheme that adaptively embeds the watermark in high frequency wavelet coefficients and offers high embedding capacity and low embedding distortion without requiring any complex lossless compression. Guo and Zhuang [10] proposed a region based DE reversible watermarking scheme for medical images to overcome the location map overhead problem of DE techniques. The scheme considers the concerns of altering all pixels for embedding; but, the manual intervention for ROI segmentation and the significant side information of multiple polygon limit the practicability of that scheme. Tsai et al. [21] presented an HS based watermark embedding scheme using a linear prediction that maximizes the embedding capacity, keeping the embedding distortion at significantly lower levels, and thereby, demonstrating its practicability for medical images.

However, similar to most of the reversible embedding, the above schemes [10], [12], [18], [21] have an image-content-dependent capacity, which results in a varying performance problem for different modality medical images. For example, an embedding scheme having such a capacity property may have a varying capacity for different images. Thus, a prior capacity estimation may be required to check if the capacity is sufficient for a given payload. In addition to that computational overhead, the overall performance of the scheme may significantly deteriorate when the estimated capacity remains insufficient, and a multilevel embedding (or re-embedding) is required. Here, a multilevel embedding re-embeds the remaining part of the payload in a watermarked image repeatedly until the required capacity is achieved. Such repeated alterations of pixels may not always incur more distortion (due to using the same LSB-plane for re-embedding), but they are more likely to deteriorate the overall embedding performance (e.g., increase the embedding time). Therefore, for embedding of the same size payload, the embedding time and level of distortion in different medical images (even of the same sizes) may not be the same. Furthermore, once the watermarked image is restored to the original image, any security protection discontinues. In addressing the above limitations in current watermark embedding schemes for medical images, we introduce a generalized embedding scheme in the following section.

III. PROPOSED EMBEDDING SCHEME

The aim of this paper is to demonstrate that the least significant border pixels in medical images can be watermarked, not only to minimize the legal and ethical concerns but also to ensure a continuous protection. We propose here an adaptive LSB (least significant bit) based watermark embedding scheme that can offer various features in addressing the conflicting embedding problems for medical images and the limitations of existing embedding schemes. We briefly describe the key features of our scheme below.

A. Features of the Proposed Scheme

1) Generalized RONI selection and embedding: Our proposed scheme avoids the existing RONI (or ROI) segmentation problems as discussed in Section III. Here, we have sought out a method to determine RONI that uses the least significant pixels and their least significant bit planes, for watermark embedding. For medical images, irrespective of their modalities, we have observed that the border pixels are generally the least
significant pixels. Therefore, we considered the border region of a medical image as RONI. This method further adaptively searches the suitable number of least significant bit planes of the RONI pixels to keep the distortion in the embedding region at a minimum level. Moreover, considering border pixels offers a general platform to work on different modality medical images. This RONI selection method, therefore, has helped us to develop a simplified and generalized embedding scheme for medical images.

2) Minimized legal and ethical concerns: Our embedding scheme considers the legal issues, and ethical concerns of medical professionals and patients, arising from the embedding distortion. Since, there is no clear cut boundary of any acceptable embedding distortion, researchers try to keep it at a minimum level, for medical images. This minimum level of distortion, however, is relative and may vary significantly for different medical image modalities and for different size payloads. Thus, an invertible distortion of reversible embedding schemes might help, but due to their limited practicability (resulting from their varying performance as discussed in Section [I] and lack of clinical validation, doctors and medical professionals have remained sceptical about considering them for medical images. As a result, keeping the ROI pixels untouched, in our embedding scheme, should minimize the concerns about altering all pixels, particularly, that are of more significance to medical or clinical uses.

3) Image-content-independent capacity: The proposed embedding scheme offers an image content independent capacity. Unlike embedding schemes with image-content-dependent capacity (discussed in Section [I]), the proposed scheme only requires capacity estimation, when there is a change in payload or image size. Consequently, the required embedding time of the proposed scheme for the same size payloads and images should remain the same and relatively less than other schemes that have an image-content-dependent capacity.

4) Flexible capacity control ability: Our scheme also introduces an adaptive capacity control method for an increasing size payload. This method aims at providing flexibility to increase the embedding capacity when required, and maintaining a minimum distortion in the embedding region, without deteriorating the performance. An embedding scheme having a limited capacity control ability often considers re-embedding, which makes the scheme relatively slower and may incur more distortion, as discussed in the last section. Our scheme attempts to minimize this problem by increasing the border width (in terms of pixels) and their LSB-planes adaptively to accommodate the increasing payloads.

5) Continuous security protection: Our proposed scheme also aims at maximizing the duration of protection by embedding the payload in an irreversible way, assuming that the watermark has been generated to achieve any required security properties (e.g., authentication, integrity verification, confidentiality). As mentioned in Section [I] any particular security properties that a watermarking scheme requires, can be obtained by deploying a suitable cryptographic technique(s). Here, a watermark could be secure as long as the used cryptographic technique is believed to be secure. Watermark embedding, however, needs to ensure that the validity of the embedded watermark is always verifiable as long as the protection is required. Unlike any reversible embedding schemes (that stop any protection when a watermarked image is restored to the original), our embedding scheme allows the watermark to remain embedded for any operational environment (e.g., medical diagnosis, clinical study and research, image archives etc.). As a result, the verifiability of an embedded watermark for the required security properties helps provide a continuous protection of the medical images, at any point of use.

In support of the above features, we will present and analyse our experimental results in Section IV. Before that, however, we discuss below the practicability and implementation of our embedding scheme for medical images with greater technical details.

B. Practicability of the Proposed Scheme for Medical Images

The increasing need for sharing medical images (for distant medical services: teleradiology, telemedicine, tele-surgery, to name a few) warrants a complementary measure that may help address the limitations of conventional security measures (e.g., file-header, hash function, encryption, etc.) [2]. To this, digital (fragile) watermarking, in a form of communication, facilitates the use of an existing suitable cryptographic technique(s). Thus, such a watermarking scheme can help address not only the rising security problems of medical images (e.g., retention and fraud, distrust and invasion of privacy, malpractice in contracts, etc.), but also several non-security problems of communication (e.g., saving memory and bandwidth, avoiding detachment etc.) [2]. Here, we have developed a fragile, blind, irreversible, LSB based (spatial domain) watermark embedding scheme—as a component function of a digital watermarking scheme. We briefly describe below some key technical properties of the proposed scheme to demonstrate how these properties can make the embedding scheme relatively more practicable for medical image applications.

1) Fragile watermark embedding: The proposed scheme is fragile. That is, it embeds a fragile watermark, which by definition becomes invalid even for the smallest modification in the watermarked images. Therefore, a fragile scheme usually requires a reliable (operating) environment to cope with the unintentional communication errors (to make sure that only a malicious modification makes the watermark invalid), for example, by using an error correction code. In addition to this requirement, however, a reversible embedding (which is also fragile) assumes a secure environment, where the users (e.g., doctors, other medical professionals) of a restored medical image are assumed to be trusted, which may not be always true in a real scenario. As a result, unlike our embedding scheme, protection of medical images remains limited for the reversible embedding schemes (considering that the watermark is used to achieve any security property). A fragile watermark also offers a high (embedding) capacity, which is required for medical images to accommodate necessary payloads for addressing some security and non-security problems. Moreover, a fragile watermark embedding is relatively simple in operation.

2) Blind detection: Blindness is a property of the watermark detector that determines whether the watermarked image can be verified independently or not, i.e., a blind detector does not require an original image (and/or watermark) as input(s). Therefore, unlike non-blind watermarking, a blind watermarking helps avoid any further security problems arising from such original information being available at the detector. However, watermark embedding and generation play important roles for a detector to work independently. Here, our embedding scheme
is designed in such a way that the detector does not require any original information to extract the embedded watermark from a watermarked image.

3) Irreversible embedding: In our proposed scheme, irreversible embedding helps with a permanent association of the watermark (to allow continuous protection of the watermarked images as discussed in Section III-A5), and makes the side information more manageable than a reversible scheme. For example, in a compression based reversible embedding scheme [3, 10], a part of the total capacity is consumed by the losslessly compressed bit-planes or ROI, which is not the case for our scheme. Our scheme does not compress any bit-planes or RONI pixels, that are used for embedding resulting in an increased effective capacity—total capacity minus side information, in bits.

4) LSB-based (spatial domain) embedding: Most of the watermark embedding schemes make use of relatively redundant bits (e.g., LSBs) of the cover images. Our proposed scheme does not operate on the whole image, rather it uses the LSB-planes of the border pixels directly. This scheme also does not depend on the perceptual content of the embedding pixels. All these ultimately help minimize the embedding time by avoiding complexities in prior capacity estimation and re-embedding like many other schemes, as discussed in section III-A.

5) Secrecy of embedding location: It is worth noting here that our scheme does not aim to achieve any security property for the embedding location, considering that a fragile watermark may not require this property. Additionally, as already mentioned before, we consider that any required security properties of the watermark are obtainable by deploying a suitable cryptographic technique(s). This should also be the case for other reversible fragile-embedding, which similarly has no secrecy of the embedding location with letting the detector know the starting point of the embedded data (e.g., the set of maxima and minima of histogram, location map, or other side information), unless the embedding algorithm is assumed to be a black-box.

C. Implementation of the Proposed Scheme

We now describe the implementation of the proposed scheme using the flow-chart illustrated in Fig. 2. For the given set of inputs: an image, I, and a watermark, W, the scheme with an initialized pair of thresholds \((T_1, T_2)\) determines the border width \((i.e., \) the number of pixels in the border that are selected as RONI), \(N_{BW}\), and the number of LSB-planes (of RONI pixels), \(N_{LSB}\), for embedding the payload, \(P\). This helps determine the optimum combination of \(N_{BW}\) and \(N_{LSB}\), for which the embedding distortion in RONI remains at a minimum level, with the capacity condition:

\[
C_{total} \geq C_p
\]

where \(C_{total}\) is the total capacity and \(C_p\) is the size of payload. Total capacity is calculated here using:

\[
C_{total} = 2N_{BW} \times (r + c - 2N_{BW}) \times N_{LSB}
\]

where \(r\) and \(c\) are the number of pixels in a row and a column of an input image, respectively.

If the capacity condition in (1) is not fulfilled, \(N_{BW}\) and \(N_{LSB}\) (initialized at value one, ‘1’) are increased by a unit step to increase the \(C_{total}\). We observed (from our experiments, which will be discussed in Section IV) that increasing \(N_{BW}\) gives higher capacity for a fixed \(N_{LSB}\) than increasing \(N_{LSB}\) for a fixed \(N_{BW}\). Therefore, firstly, \(N_{BW}\) is increased successively (after checking the capacity condition each time) up to its given maximum limit, \(T_1\). Then, \(N_{LSB}\) is increased by a unit step, when \(N_{BW} = T_1\). This way, until the condition in (1) is fulfilled, \(N_{BW}\) and \(N_{LSB}\) are increased up to their maximum limits \(T_1\) and \(T_2\), respectively. In the above selection method of \(N_{BW}\) and \(N_{LSB}\), the threshold pair \((T_1, T_2)\) has an important role to select the RONI, and to control the capacity adaptively for an increasing size watermark. For all modality medical images, there should be a well defined \((T_1, T_2)\) that helps accommodate the watermark used for medical image applications. However, for a given \((T_1, T_2)\), if the capacity condition is not satisfied (i.e., no \(N_{BW}\) and \(N_{LSB}\) are found for the given watermark and image), a user prompt is required to update \((T_1, T_2)\) as shown in Fig. 2. Otherwise, the input image and/or the watermark can be reconsidered.

1) Watermark embedding: Once the capacity condition is satisfied, the payload is embedded using the embedding function, \(E(\cdot)\) as given in [2]. The function \(E(\cdot)\) replaces the bits in the selected LSB-planes of the selected border pixels sequentially. However, in order to extract the watermark independently, a detector requires \(N_{LSB}, N_{BW}\), and the size of the watermark, \(C_w\). These values are formatted in a predefined frame of \(Load\) using a function, \(Format(\cdot)\), as given in [4]. An example of \(Load\) data-frame is shown in Fig. 4(b) for a
2) Watermark extraction: The embedded payload is extracted from a watermarked image as a part of detection. As illustrated in Fig. 3, a detector is initialized with the predefined Load data-frame. Then the $N_{BW}$, $N_{LSB}$, and $C_w$ are obtained from the extracted Load data from the input watermarked image, $I$. To extract the embedded watermark, $W$, the detector then extracts the $C_w$-bit sequentially from the $N_{BW}$ border pixels of the $N_{LSB}$ LSB-planes. Here, the extracted $C_w$-bit are the embedded watermark, assuming no bit-error occurs.

3) An example of how the proposed scheme works: To exemplify the above embedding and extraction techniques, we consider an instance of our embedding scheme as illustrated in Fig. 5. An 8-bit image of size 10x10 is shown sliced into its 8-bit planes along Z-axis (with increasing order of significance, downward). Let, a 150-bit watermark (i.e., $C_w = 150$) is to be embedded, where $T_1 = 2$ and $T_2 = 4$. Assuming a 32-bit Load data frame (i.e., $C_l = 32$), $P$ is calculated, i.e., $C_p = 150 + 32 = 182$. Now, for the given $T_1$ and $T_2$, suitable $N_{BW}$ and $N_{LSB}$ are determined for embedding $C_p$ bits. Here, the internal computations are:

when, $N_{BW} = 1$ and $N_{LSB} = 1$, $C_l = 36$  
$N_{BW} = 2$ and $N_{LSB} = 1$, $C_l = 64$  
$N_{BW} = 2$ and $N_{LSB} = 2$, $C_l = 128$  
$N_{BW} = 2$ and $N_{LSB} = 3$, $C_l = 192$

The embedding function finds $C_{total} > C_p$ for $N_{BW} = 2$ and $N_{LSB} = 3$, and stops checking the capacity condition. As shown in Fig. 4(b), a 32-bit Load is computed for $N_{BW} = 2$, $N_{LSB} = 3$, $C_w = 150$. (In this example, a 32-bit Load data-frame seems to be superfluous for a 150-bit watermark. That frame allows up to $2^{16} = 65536$-bit watermark in practice which needs to be redefined for any higher size watermark.) Then the 182-bit $P$ is computed by concatenating the Load and $W$, which is finally embedded by replacing the LSBs in RONI in a predefined order (which needs to be known by the detector). We consider starting the embedding from $f(0, 0, 1)$ to $f(5, 8, 3)$ occupying 182-bit sequentially (e.g., outer border pixels first, continuing up to $N_{BW}$ pixels of all LSB-planes with increasing significance up to $N_{LSB} = 3$, counter-clockwise). Once the payload, $P$ is embedded, the watermarked image, $I$ is output.

On the other hand, to extract the watermark, $W$ from a given watermarked image, $I$, a detector first obtains the embedded Load information: $N_{BW} = 2$, $N_{LSB} = 3$, and $C_w = 150$. Then, from the next bit-location of Load data-frame, 150 bits are extracted from 3 LSB-planes of 2 border pixels, in their embedding order, and $W$ is yielded.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

In what follows, we present the performance of the proposed scheme and then we compare its performance with that of a reversible scheme [21]. The choice of the scheme [21] is based on the fact that it has received much attention recently for medical image applications. We used a set of 370 medical images of different modalities (e.g., CT, MR, X-ray, US, etc.) and of different file formats (e.g., DCM, DC3, JPG, BMP,
etc.). Image sizes ranged from 196 × 258 to 600 × 600, and image bit-depths are of 8-bit and 16-bit. A watermark is considered as a set of binary arrays, \( \{0, 1\}^t \). All necessary simulations were carried out in MATLAB (R2012a-7.140.739) using an Intel Core i5 3.2GHz CPU. We have experimented with the border width, \( N_{BW} \in \{1, 2, 3\} \) and the bit-plane, \( N_{LSB} \in \{1, 2, \ldots, 8\} \) for performance evaluation of the proposed scheme.

As expected, we observe that the higher the values of \( N_{BW} \) and/or \( N_{LSB} \), the higher the capacity of the proposed scheme. Interestingly, we also notice in Fig. 6(a) that the capacity increases more with an increase of \( N_{BW} \) than of \( N_{LSB} \), for \( N_{LSB} = 2 \) or higher. To illustrate this, let us consider an instance from the Fig. 6(a) when \( N_{BW} = 2 \), and \( N_{LSB} = 4 \), capacity is approximately 15 Kbit. With an increase of only \( N_{BW} \) by one pixel, the capacity increases to 22 Kbit. Instead of doing that, however, if we only increase \( N_{LSB} \) by one bit plane, we get the capacity of about 19 Kbit, which is lower by 3 Kbit than the previous capacity obtained for increasing \( N_{BW} \). This capacity difference becomes successively higher for the higher values of \( N_{BW} \) and \( N_{LSB} \). Such an effect of increasing \( N_{BW} \) and \( N_{LSB} \) on the capacity suggests that for higher capacity, one should consider increasing \( N_{BW} \) first up to \( T_1 \), prior to increasing \( N_{LSB} \) to its next level as shown in Fig. 2. We also notice in Fig. 6(c,d) that increasing \( N_{BW} \) for a fixed \( N_{LSB} \), while gives higher capacity, causes relatively low distortion in the embedding region.

We note here that the above choice of increasing capacity in terms of \( N_{LSB} \) and \( N_{BW} \) are made based on the fact illustrated in Fig. 6. Here, the capacity difference depends not only the \( N_{LSB} \) and \( N_{BW} \), but also the size (i.e., number pixels in rows and columns) of an image. Therefore, as Fig. 6 represents the average performances of the proposed scheme for a large set of test images, the above mentioned approach in increasing capacity should be efficient in an operational environment. Although the approach may not be always similarly efficient for different (particularly, very low) size of medical images, it may still be useful.

However, an increase in either \( N_{BW} \) or \( N_{LSB} \) has a declining effect on the computational efficiency and image quality of the proposed scheme. Here, computational efficiency is evaluated in terms of embedding time in that the higher computational complexity results in the higher embedding time, and thus an embedding scheme becomes the lesser computationally efficient. As shown in Fig. 6(b) embedding time increases for the respective increases in \( N_{BW} \) and \( N_{LSB} \), which means that the higher capacity one needs, the higher time an embedding function takes.

On the other hand, the image quality is evaluated in terms of PSNR–peak signal-to-noise ratio and MSSIM–mean structural similarity index [22], respectively. PSNR estimates the perceived errors, and thus a PSNR value does not indicate any particular subjective quality of an image [23]. Although the relative PSNRs for different values of \( N_{BW} \) and \( N_{LSB} \) of the proposed scheme seem to be meaningful in Fig. 6(c), we will see below in Fig. 7 how PSNR fails to represent image quality degradation for with Tsai et al. scheme [21]. Nonetheless, with MSSIM—a particularly designed metric to measure the similarity of perceptual contents—Fig. 6(d) illustrates a more reasonable relationship of image quality.

As illustrated in Fig. 6(d), image quality degradation for different values of \( N_{BW} \) and \( N_{LSB} \) suggests a boundary for using the number of bit-planes, \( N_{LSB} \). This means that up to 4 LSB-planes, the impact on quality of the border pixels remains barely noticeable, which gives a maximum capacity of about 23 Kbit for \( N_{BW} = 3 \). Whereas, 20 Kbit capacity is presumably found sufficient for our watermarking objectives (i.e., the authentication and integrity verification) by deploying cryptographic techniques, as discussed in Section III-A5. (For higher capacity, however, a higher border width can be considered.) With this consideration, we have experimented with \( N_{BW} \in \{1, 2, 3\} \), and \( N_{LSB} = 4 \) for the performance comparison.

We have used a set of 150 same size images of different modalities to compare the performance of the proposed scheme with the scheme in [21]. Fig. 7 illustrates the performances of the both schemes for different parameters over (i) the test set of images arranged in no particular order in Fig. 7(a–d), and (ii) the variance of the test set of images in Fig. 7(e–h). In both cases, a consistent and image content invariant characteristics of the proposed scheme for the performance parameters (e.g., capacity, embedding time, and image quality degradation) are evident. A varying performance of the Tsai et al. scheme, in contrast, indicates that without knowing the image modality and content, it may be difficult to know how well the scheme can perform, although that variations are suggestive of their certain ranges. To get an overall picture, average values of the performance parameters are also given in Table I.

We also notice that the average capacity of Tsai et al. scheme is about 84 Kbit as given in Table I and also shown in Fig. 7(a, e), which is much higher than the maximum capacity level of our scheme for \( N_{BW} = 3 \), and \( N_{LSB} = 4 \). However, unlike our scheme, any smaller size payloads than the available capacity do not mean that the distortion level or the embedding time will be lower for the Tsai et al. scheme. (Whereas, any higher size payloads may increase the embedding time and distortion level as discussed in Section I) Besides, we have already mentioned above and also in Section III-A2 that the proposed scheme allows an increasing \( N_{BW} \) and \( N_{LSB} \) (up to the predefined thresholds, \( T_1 \) and \( T_2 \), depending on

<table>
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<th>Method</th>
<th>Capacity (Kbit)</th>
<th>Embedding Time (s)</th>
<th>PSNR (dB)</th>
<th>MSSIM</th>
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<td>Tsai et al. [21]</td>
<td>84.023</td>
<td>0.2951</td>
<td>54.87</td>
<td>0.9899</td>
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<td>14.18</td>
<td>0.0020</td>
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<td>Proposed (( N_{BW} = 3 ))</td>
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<th>Capacity (Kbit)</th>
<th>Embedding Time (s)</th>
<th>PSNR (dB)</th>
<th>MSSIM</th>
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<td>CT</td>
<td>ours</td>
<td>0.0027</td>
<td>51.79</td>
<td>0.9899</td>
<td>0.9999</td>
</tr>
<tr>
<td>X-ray</td>
<td>ours</td>
<td>0.0025</td>
<td>55.14</td>
<td>0.9914</td>
<td>0.9998</td>
</tr>
<tr>
<td>RF</td>
<td>ours</td>
<td>0.0024</td>
<td>63.96</td>
<td>0.9901</td>
<td>0.9999</td>
</tr>
<tr>
<td>US</td>
<td>ours</td>
<td>0.0023</td>
<td>80.46</td>
<td>0.9988</td>
<td>1.0000</td>
</tr>
<tr>
<td>MG</td>
<td>ours</td>
<td>0.0014</td>
<td>83.66</td>
<td>0.9989</td>
<td>0.9999</td>
</tr>
<tr>
<td>DSA</td>
<td>ours</td>
<td>0.0026</td>
<td>46.50</td>
<td>0.9941</td>
<td>0.9999</td>
</tr>
</tbody>
</table>

* for \( N_{BW} = 3 \) and \( N_{LSB} = 4 \)
Fig. 6: Performance evaluation of the proposed scheme for increasing values of $N_{BW}$ (up to 3) and $N_{LSB}$ (up to 8): (a) capacity (Kbits), (b) embedding time (seconds), (c) PSNR (dBs), and (d) MSSIM. (Averages are calculated for 370 images of different modalities and sizes.)

Fig. 7: Performance comparison of the proposed scheme with Tsai et al. [21], where $N_{BW} \in \{1, 2, 3\}$ and $N_{LSB} = 4$: (a–d) for the same size images, (e–h) for the variance of same size images, (a,e) capacity (Kbits), (b,f) embedding time (seconds), (c,g) PSNR (dBs), and (d,h) MSSIM.

the constraint of other parameters) to increase the capacity. Whereas, Tsai et al. scheme does have a fixed capacity for one level embedding (and may require re-embedding resulting in significant performance issues as discussed in Section II). The proposed scheme also takes only a few milliseconds to embed the same size of payload as shown in Fig. 7(b, f), and is found to be about one hundred times faster than the Tsai et al. scheme (although the embedding time may vary with different programming scripts of an embedding function). Similarly, Fig. 7(d, h) indicates that the MSSIM of the proposed scheme remains consistently higher than that of Tsai et al. scheme.

Unlike MSSIM, however, Fig. 7(c, g) illustrates that PSNR is not a suitable subjective quality measure as mentioned earlier in this section. Particularly, for the proposed scheme that aims at maintaining a good quality in the embedding region, while preserves the ROIs completely. This means that the proposed scheme keeps all the pixels in the watermarked images untouched except the border pixels, whereas Tsai et al. scheme operates on the whole image. But, for the proposed scheme, image quality degradation in the embedding region (i.e., the border pixels) has quite an impact on the PSNR values. Consequently, PSNR values for the proposed scheme seem to be lower than that of the Tsai et al. scheme. Further, the perceived errors may vary with the perceptual content of different modality medical images. Thus, the PSNR values appear to be random even for the same embedding locations, payload, and image size, for the proposed scheme.

Performance of a watermark embedding scheme may also significantly vary with the medical image modalities. Image modality-wise performances for different parameters are presented in Table II where we observe the variation in overall performances more precisely between ours and Tsai et al. scheme. We note that the average values for different performance parameters are given for the test set of 370 images of different sizes. Similar to Fig. 7(a) a relatively consistent performance of the proposed scheme is evident in Table II irrespective of image modalities.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced an approach for utilizing least significant border pixels and their least significant bit-planes for medical image watermarking. We, thereby, proposed a new watermark embedding scheme for medical image applications. The technical properties of the scheme, discussed in this paper, are demonstrative of its practicability for all modality medical images. Our fragile, irreversible, spatial domain, LSB based embedding thus offers a set of attractive features to address the limitations of many other schemes. The legal and ethical
concerns, ROI/RONI segmentation problem, discontinuity in security protection are such a few common limitations. The proposed scheme show a great promise to address all these major limitations of existing schemes, for medical images.

Performance of the scheme is evaluated and analysed, and compared with a prominent reversible scheme. Experimental results have shown that the proposed scheme has a significant computational efficiency due to mainly (i) avoiding ROI/RONI segmentation complexities, and (ii) having an image-content-independent capacity. An image-content-dependent capacity can make the prior capacity estimation and capacity control more complex for many schemes. (A prior capacity estimation and capacity control are required to manage the embedding of an increasing size payload.) Our scheme avoids such complexities, and maintains a good image quality in the RONI, while keeping all other pixels untouched to minimize legal and ethical concerns.

Future work. Although our results of the embedding scheme are promising for medical image applications, the work presented here has some limitations that raised the following questions in need of further investigation.

(i) We considered only one reversible embedding scheme for performance comparison. In our follow-up work, we will continue our experimentation to compare the performance of the proposed scheme with some other existing schemes received attention for medical image applications.

(ii) We did not consider bit-depth here for performance evaluation, since the embedding capacity of the proposed scheme is independent of the image bit-depth. However, other performance parameters (e.g., watermarked image quality) may vary for different bit-depth images, which is in need of further experimentation, and will be considered in our follow-up work.

(iii) Additionally, the proposed scheme has only been tested for the border width of up to three pixels (i.e., up to $N_{BW} = 3$), since it seemed sufficient (in terms of $C_{total}$) for our future watermarking objectives (i.e., authentication and integrity verification of medical images). However, a further investigation on an increasing border width (e.g., for up to $N_{BW} = 10$) and its effect on overall embedding performance for different modality medical images is required for other watermarking objectives (e.g., annotation of EPR).

ACKNOWLEDGMENT

The assistance of Dr Frank Gaillard (Administrator, Radio-pedia.org) for the test medical images, Prof. Anthony Maeder (University of Western Sydney) for making useful suggestions regarding medical image datasets and their web-links, and Dr Beat Schmutz (IHBi, Queensland University of Technology) for providing MR and CT test images, are noted with gratitude.

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