Introducing Capacity Surface to Estimate Watermarking Capacity

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Abstract
One of the most important parameters in evaluating a watermarking algorithm is its capacity. Generally, watermarking capacity is expressed by bits per pixel (bpp) unit measure. But this measure does not show what the side effects would be on image quality, watermark robustness and capacity. In this paper we propose a three dimensional measure named Capacity surface which shows the effects of capacity on visual quality and robustness. By this measure we can objectively find the amount of degradation and robustness for different capacities. Our experimental results are compatible with the previous related works in this field (about 20% tolerance) while provide more flexibility for capacity estimation in different conditions.

***Keywords*—**Watermarking Capacity, Capacity surface, Bits per pixel.

I. INTRODUCTION

Determing the capacity of watermark in a digital image means finding how much information can be hidded in it without perceptible distortion, while maintaining watermark robustness against usual signal processing manipulations and attacks. This topic has an important role in designing effective watermarking algorithms. Knowing the watermark capacity for a given image is useful to select a watermark with a size near the capacity in order to improve the robustness or repeat a smaller size watermark until reaching the capacity.

However, calculating watermark capacity in images is a complex problem, because it is influenced by many factors. But generally, there are three main parameters in watermarking: capacity, quality, and robustness. These parameters are not independent and have side effect on each other. For example, improving watermark robustness by repeating watermark bits decreases the image quality; or quality enhancement is achieved by decreasing the capacity and vice versa.

Several works on watermarking capacity have been presented. Servetto in [1] considered each pixel as an independent channel and calculated the capacity based on the theory of Parallel Gaussian Channels (PGC). Barni's research is focused on the image watermarking capacity in DCT (Discrete Cosine Transform) and the DFT (Discrete Fourier Transform) domain [2]. Moulin studied a kind of watermarking capacity problem under attacks [3] [4]. Lin presented zero-error information hiding capacity analysis method in JPEG compressed domain using adjacency reducing mapping technique [5][6]. Cagan analyzed a special kind of capacity in J2J (Jpeg to Jpeg compression) [7]. Voloshynovisky studied some effects of image modeling on capacity and introduced the Noise Visibility Function (NVF) [8-10]. Zhang in [11-13] explained some properties of host image and its effect on watermarking capacity. We shall note that, these methods use different approaches to find the capacity. However, the estimated capacity values have a diverged range from 0.002 bpp (bits per pixel) to 1.3 bpp [13].

However in all related previous works, the watermarking capacity has been expressed by bits per pixel (bpp) unit measure. Although this measure gives a good sense about watermark capacity, visual quality and robustness of watermarked image are neglected here. When we say that an image has a capacity for example about 0.01 bpp and the image has 10000 pixels we can simply calculate the watermark capacity as 10000×0.01=100 bits. But in this case, we cannot estimate how much degradation will be imposed on image or if we use fewer bits, how much improvement in quality will be achieved. On the other hand, if the number of bits used for watermarking is more than the above mentioned capacity (e.g. 110 bits), how much degradation in quality will be imposed.

Of course in another side, the watermarking robustness is an emergent topic. Robustness in watermarking has been generally identified with probability of decoding error or resistance against watermark removal. This topic is completely bypassed with bpp unit.

In our previous work [14] a new measure introduced for watermarking capacity that considers the visual quality of watermarked image as well. This new measure was called Capacity Curve and we showed that it provides much useful information about image capacity. However robustness was not analyzed by the capacity curve.

In this paper, we introduce a three dimensional capacity measure, named *Capacity surface*. This measure helps us to estimate watermark capacity within a predefined constraint on image quality and

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robustness. This measure considers all three effective parameters in watermarking and will be a suitable measure for different applications in watermarking.

The rest of paper is organized as follows. In section 2 a description of our previous work that considers capacity and image quality. In section 3 we explain the capacity surface that considers capacity, quality and robustness simultaneously. In section 4 and 5 experimental results and comparison with other works is presented. Finally conclusion is provided in section 6.

II. Capacity curve

In our previous works on capacity estimation we found that it is not suitable to express capacity by bpp measure. Because it does not consider degradation of image quality or robustness. In [14] we proposed capacity curve that could be considered as a two dimensional measure to estimate watermark capacity. By this measure we can estimate quality degradation in any watermark size or find the suitable watermark size in a predefined image quality. The curve for each image is calculated by interpolation between quality degradation values of 100 different watermarked versions of that image.

Fig 1 shows three standard images: Moon, Lena and Baboon. In Fig 2 the calculated capacity curves of these images are shown. Horizontal axis stands for image quality explained by SSIM (Structural Similarity Index Measure) and vertical axis is for capacity in allowable mean pixel value modification.

Fig. 1. (a) Moon, (b) Lena, (c) Baboon.

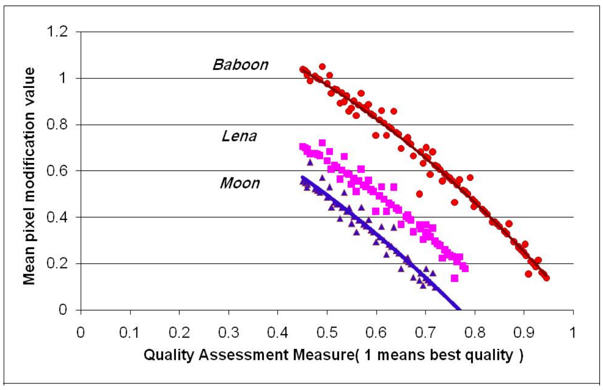

Fig. 2. Capacity curves of images in Fig. 1

SSIM is a state of the art measure for image quality assessment which considers structural similarity in images. This measure is fully described in [15] [16]. As it is obvious in Fig.2, in any image quality we can estimate the capacity or in each capacity we can estimate image quality degradation. Our experimental results showed the applications of this measure in watermarking and steganography.

Although this measure does not consider the relation between watermarking and robustness, it is useful to find a measure which considers triple relation between capacity, quality and robustness. In the following section we will discuss about this subject.

III. Capacity surface estimation

In this section we describe our idea about capacity surface and introduce a method to find it. We refer to the fact that watermarking capacity is affected both by image quality and robustness. For this reason, we propose to estimate the capacity of each image under specific image quality and watermark robustness. Fig 3 shows a typical capacity surface of an image. As it is obvious in this figure, we can estimate capacity in mean pixel modification within any predefined quality and robustness level.

If we find the capacity surface of an image, it would be possible to estimate the capacity of each image in any quality and robustness constraint. This means that, we can find the size of watermark that gives us the suitable robustness and desired quality degradation.

To find the capacity surface of an image, we must implement a specific watermarking algorithm and analyze its robustness and quality degradation.

But determining the watermark robustness is not so easy, mainly because of the following two reasons.

1) There is not a standard measure to evaluate robustness objectively, while for evaluating image quality degradation there are standard measures like PSNR or SSIM.

2) Watermarking robustness is highly application dependent and it is completely affected by watermarking method.

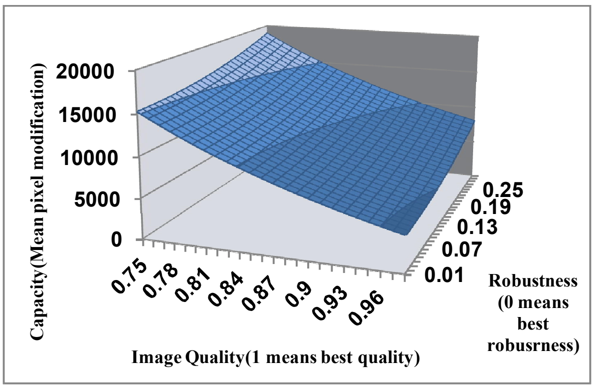

Fig. 3. A typical capacity surface

Each watermarking method is robust against some modifications and is fragile against others. Even attacks in benchmarks like Stirmark [17] [18] are not necessarily acceptable by researchers in this field. Therefore, calculating robustness can be employed only on a specific watermarking algorithm. This means that for any image we can find a capacity surface according to the specific watermarking method. For our experiments we selected three famous methods in different domains: amplitude modulation in spatial domain [19], Cox in DCT domain [20] and Kundur in wavelet domain [21].

For each watermarking algorithm we used 100 different random patterns as watermark in different sizes (64, 128, 256 and 1024 bits). After that, we used additive Gaussian noise with different variance as a typical attack [2, 3 and 13]. In this simulation the attack power is proportional to noise variance.

It must be noted that in some works, Gaussian noise is used to simulate watermark embedding in general [3, 9]. But for watermark embedding simulation, the noise amplitude and variance is small. In other words, in watermark embedding the image quality degradation is low. This is natural because watermarking doesn't produce obvious artifact in image. But in attacks simulation, variance of noise is much higher and quality degradation is more than embedding phase. This means that the modification in channel is much more than the manipulation in embedding process in transmitter side. In some papers allowable modification in embedding is named D_1 and the allowable modification in channel is named D_2. Usually $D_2=5\times D_1$ or $D_2=10\times D_1$ [3, 9].

We used Bit Error Rate (BER) parameter to estimate the watermark robustness. BER is the percentage of error bits extracted from image at the receiver side after channel attacks. In other side, we used SSIM for quality degradation.

IV. EXPERIMENTAL RESULTS

As we noted in previous section, to compare results and showing the capacity surface usefulness, we selected three famous watermarking algorithms: amplitude modulation in spatial domain [19], Cox algorithm in DCT domain [20] and Kundur method in wavelet domain [21]. For simplicity, we refer to these algorithms as Spatial, DCT and Wavelet. We used standard images in Fig.1 for our experiments. The surface is calculated by noise addition process as mentioned in previous section. The results are shown in Figs 4, 5 and 6 for Spatial, DCT and Wavelet algorithms, respectively.

As it is obvious from these surfaces, decreasing robustness and image quality will increase capacity. In other side, in high robustness and high quality, the capacity decreases. With capacity surface we can find the precise relation between capacity, image quality and robustness for a specific image and a watermarking algorithm.

The most drawback of capacity surface is its dependency to a specific watermarking algorithm. This may restrict the application of capacity surface. In the following, we will show that capacity surface is approximately unique for specific image and it does not have a high dependency to the watermarking algorithm.

First, with a look at capacity surfaces of specific image (like Lena) in different watermarking algorithms in Figs 4, 5 and 6, we understand that capacity surfaces for an image in different algorithms are very similar to each other. For better comparison, the capacity surfaces of Lena in different algorithms are shown in Fig 7.

As it is shown, the maximum and minimum values of capacity and skew of surfaces are very close to each other in different algorithms.

In another experiment we used DCT capacity surface to estimate capacity values in predefined conditions of image quality and robustness and compared them with real capacity values calculated by Spatial and Wavelet surfaces. Table 1 shows some samples of comparison between real values and estimated value with DCT surface.

The computed mean error values of real capacity in different conditions (image quality range [0.75,1] by SSIM measure and robustness [0, 0.3] by BER measure) in Spatial and Wavelet algorithms by their capacity surfaces and the estimated values by DCT surface in is about 8%. This means that, the capacity surface in one watermarking method (here DCT surface) can be used for other methods as well, while the tolerance of error is about 8% which is acceptable in real applications.

Of course it must be noted that using one specific capacity surface for other methods is acceptable if we model all image deformations and attacks with additive white Gaussian noise. But if we are interested in some specific attacks, we must analyze algorithm for those attack.

V. COMPARISON WITH PREVIOUS WORKS

In this section we compare our results with the previous related works in this field. Unfortunately there are not many reports on image capacity, and we used the results in [3] by Moulin and [9] by Voloshynovisky. Moulin has used an autoregressive image model with predefined allowable quality degradation on cover image under channel attack. Voloshynovisky introduced a stochastic non stationary image model who named it edge process model and calculated watermarking capacity under the same condition as Moulin reported in [3]. Naturally these works have reported capacity in bits per pixel (bpp) unit measure.

Since the capacity surfaces are in pixel modification unit, therefore we must change them to bits per pixel unit to be able to compare our results with the related works. We can do this by assuming that the pixel modification could happen in its least significant bits. Then we can estimate the capacity in bpp unit by calculating the logarithm (base 2) of pixel modification value in each level of image quality (i.e. different SSIM values).

For example, in a specific value of quality measure (SSIM) and robustness(BER), if according to capacity surface, in average, 8 units of modification is allowed in gray level, then, the mean capacity in *bpp* = $\log_2^8 = 3$.

For this reason we first calculate the capacity in bits per pixel for each image in a specific quality and robustness. After that we can compute the total capacity in bits by multiplying the capacity in bpp unit to the number of pixels in image (in our experiments

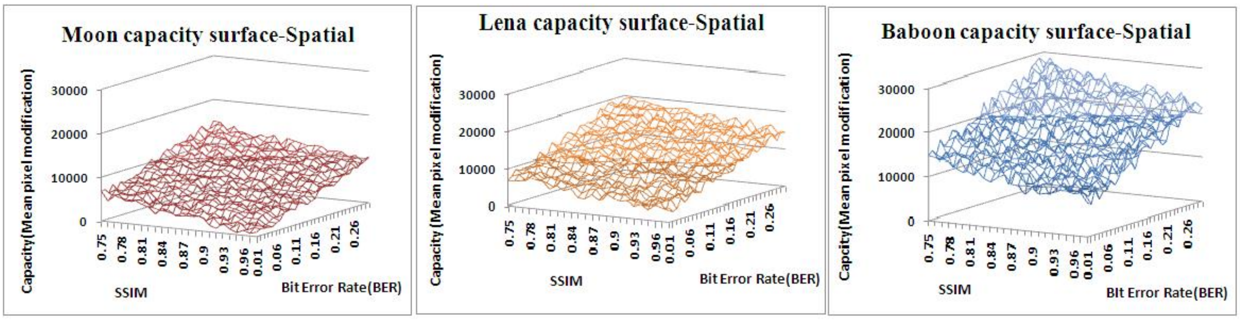

Fig. 4. Capacity surfaces of images in Fig1 in Spatial watermarking algorithm.

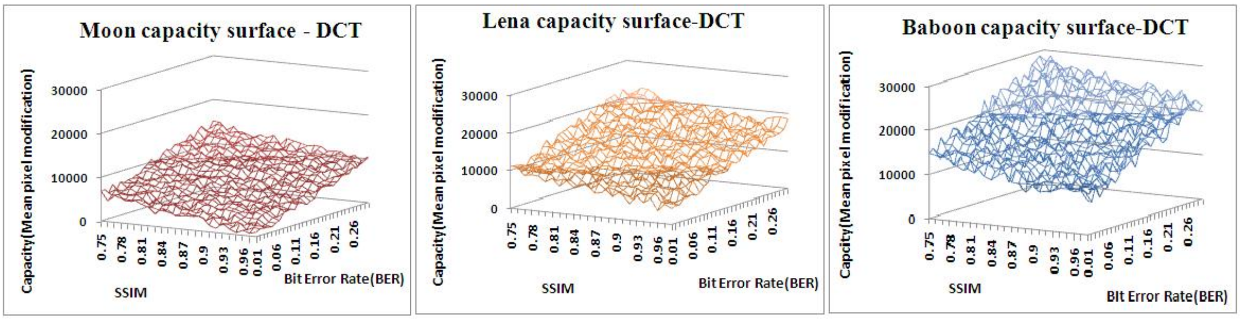

Fig. 5. Capacity surfaces for images in Fig1 using DCT watermarking algorithm

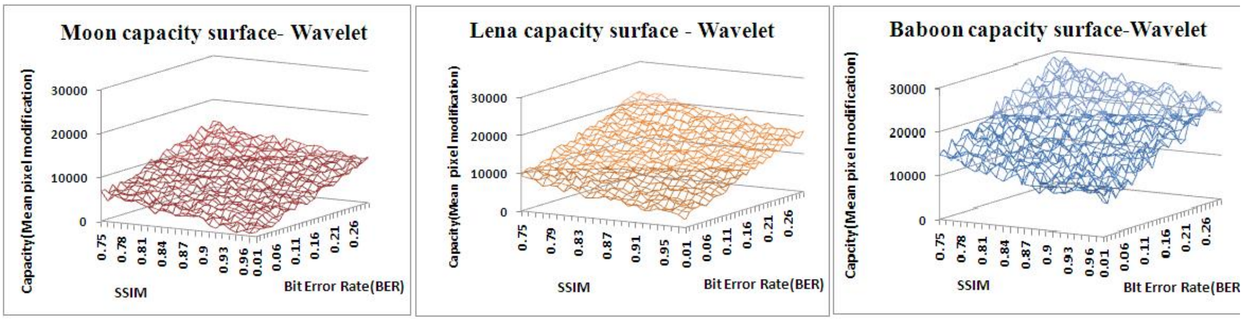

Fig. 6. Capacity surfaces of images in Fig1 in Wavelet watermarking algorithm.

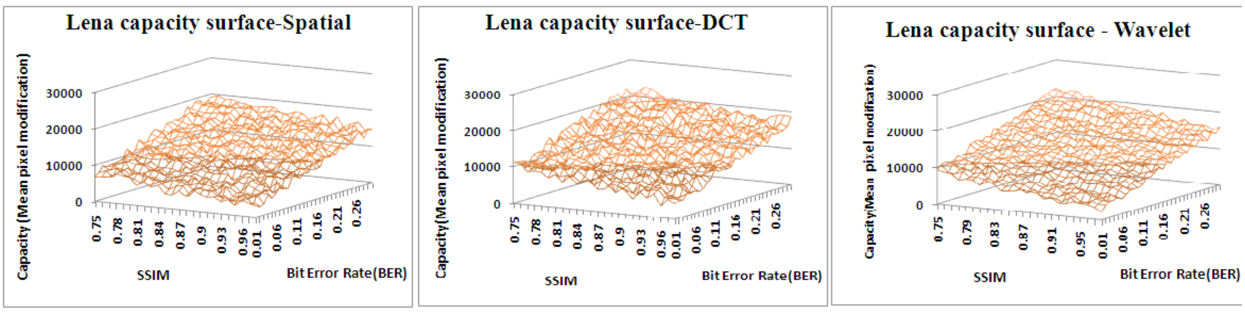

Fig. 7. The capacity surfaces of Lena, compared in different watermarking algorithms.

all images are 512×512). Table 2 shows the comparison results for some standard images.

Note that our values for image capacities have a linear correlation with computational analytic methods such as Moulin and Voloshynovisky. The amounts of tolerances shown in Table.2 are in acceptable range, as similar works in this filed have reported similar values [13].

It is essential to remember that the previous works on capacity are restricted to a predefined value of quality degradation and robustness. But we showed that the capacity can be estimated in a broad range of different visual qualities and robustness by capacity surface.

VI. CONCLUSION

Finding watermark capacity of images has an important role in selecting the appropriate watermark size within predefined visual quality and robustness. In watermarking literature, the only measure for this purpose is bits per pixel (bpp) which shows how many bits can be embedded in each pixel of image. The weak point of this measure is its lack of considering the visual quality and robustness. Measuring watermarking capacity by bpp has an impact on effectiveness of this measure because capacity, quality and robustness are three important factors in watermarking and we should not analyze these factors independently.

In this paper we proposed a three dimensional measure (Capacity surface) to estimate watermarking capacity by considering both the image quality and its robustness. For estimating capacity surface we used additive Gaussian noise with different variances to model the channel attacks. Our results show that if attacks and deformations could be considered as additive noise, the capacity surface of one image in different watermarking algorithms are very similar to each other and finding one capacity surface for an image in specific algorithm can be used in different algorithms. Of course if robustness against some specific attacks is important, then the capacity surface must be calculated for that particular watermarking algorithm. However as we cannot consider all watermarking algorithms, then we can calculate capacity surface of an image in specific algorithm and use it for other watermarking methods.

This means that watermarking capacity is highly depended to image content instead of watermarking algorithms. In any image, using capacity surface we can estimate watermarking capacity in a predefined quality and robustness with an acceptable preciseness. This is achieved without considering the watermarking domain or algorithm.

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TABLE I

Some Sample Comparison of Estimated Capacity by DCT Capacity Surface and Its Real Values in Different Algorithms

Quality (SSIM)	*Robustness (BER)*	*DCT value*	*Spatial value*	*Spatial error %*	*Wavelet value*	*Wavelet error %*
0.7500	0.0300	10545	9217	13	9800	7
0.7600	0.0400	10237	8910	13	10090	1
0.7700	0.0500	10073	9594	5	9506	6
0.7800	0.0600	9565	10299	8	10658	11
0.8200	0.0900	11886	10635	11	11332	5
0.8500	0.1100	11698	10263	12	10112	14
0.8900	0.1900	13414	12856	4	12925	4
0.9200	0.2000	14898	13018	13	13303	11
0.9500	0.2500	14344	14893	4	13828	4
MEAN				**9**		**7**

TABLE II

COMPARISON OF OUR CAPACITY RESULTS (CAPACITY SURFACE) WITH OTHERS [3][9].

("---" *MEANS THAT THE CAPACITY FOR THESE IMAGES WERE NOT REPORTED*)

Image	**Allowable modification (D_2=5×D_1), Values in bits** *Moulin*	*Voloshyno-visky*	*Capacity surface*	**Capacity surface Tolerance** *Moulin*	*Voloshyno-visky*
Lena	39817	31855	43700	9%	37%
Barbara	---	54632	60500	---	10%
Pepper	52034	---	57800	11%	---
Baboon	96532	80592	109600	13.5%	%35

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