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A communication system model for digital image watermarking problems

Pei-Chun Chen, Yung-Sheng Chen, and Wen-Hsing Hsu

Abstract—**The Internet has become the main media for sharing multimedia data, such as images, video, and audio. The ease of making exact copies of the multimedia data has urged the need for copyright protection. Digital watermarking is one of the ways to protect the copyright of the multimedia data, by embedding information of the owner or the intended user to the multimedia data. Prior work on digital watermarking has mainly focused on realizations of the techniques. In this paper, we analyze the digital watermarking problems in a theoretical point of view. More specifically, we explain performance issues in digital watermarking problems by digital communication theory. Capacity, imperceptibility, and robustness are all included in this framework. An adaptive-coding-rate watermarking scheme based on spread spectrum communications is designed for verifying the proposed framework.**

Index Terms—**Digital image watermarking, digital communication, channel capacity, spread spectrum.**

I. INTRODUCTION

WITH the prevalence of the Internet, more and more digital data can be accessed via the network. Internet users can transmit and store images, videos, and audio without offering appropriate credits to the creator. This hinders creator from sharing his works in the Internet. Digital watermarking technique is a solution to the copyright protection problem of digital media. In addition to copyright protection, digital watermark has various other applications, such as recipient marker, image fingerprinting (authentication), hidden annotation, and secret communication.

In 1994, van Schyndel et al. [1] changed the LSB of an image to embed an *m*–sequence watermark. Since then, more and more researchers studied digital watermarking problem. Digital watermarking technique evolved from how to embed a watermark in an image to how to improve the robustness of the watermark. However, there lacks complete mathematical analyses on performance of watermarking techniques. The test results applied to some specific images were not convincing enough either. In this paper, an analysis of digital image watermarking problem using concepts from digital communications is presented.

In general, watermark can be embedded in *spatial domain* or *transform domain* of an image. In the spatial domain approach, such as [1], [2], the pixel value of an image is modified to embed watermark information. In the transform domain approach, such as [3], some transform is applied to the original image first. The transform applied may be DFT, DCT, DWT, etc. The watermark is embedded by modifying the transform domain coefficients. Empirically, the transform domain approaches are more robust against noise or attack.

Digital watermarking has many applications. Different applications has different requirements. There are no general requirements for all watermarking problems. In this paper, we concern about copyright protection application of image data. The concepts discussed can apply to other media such as video as well. According to [4], requirements of copyright protection watermark include but are not constrained to (1) public watermark, (2) imperceptibility (perceptual transparency) of an invisible watermark, (3) maximal capacity, and (4) robustness against image manipulations. The later three criteria, *imperceptibility*, *maximal capacity*, and *robustness*, can not be achieved at the same time. The reason for the conflict is revealed by the formula derived in Section II.

Two ways of analyzing the criteria conflict in a watermarking problem are presented in Section II. One is from the *channel capacity* point of view, the other calculates the *probability of error* of a detected watermark under some level of noise which is caused by image manipulations. In Section III, we propose a watermarking scheme and give an experiment to show the validity of the derived formula in Section II. Finally, Section IV concludes the paper with future work.

II. MODELING OF DIGITAL IMAGE WATERMARKING PROBLEM

As outline in [5], watermark insertion and detection is similar to information insertion and detection in a communication system. Watermark information is the signal the sender intends to deliver to the receiver on the other end of the communication system. Such watermark information is embedded into its carrier, the original image, to become the watermarked image. The watermarked image can be stored or transmitted, and might possibly be modified or corrupted. At the receiver side, watermark information is to be detected from the possibly corrupted watermarked image. The whole watermark system is illustrated in Fig. 1.

This watermark insertion and detection model regards the watermarking problem as a spread spectrum digital communication problem. Watermark is the message, while the original image is the channel. In the watermark detection stage, the original image acts as a noise to the watermark message.

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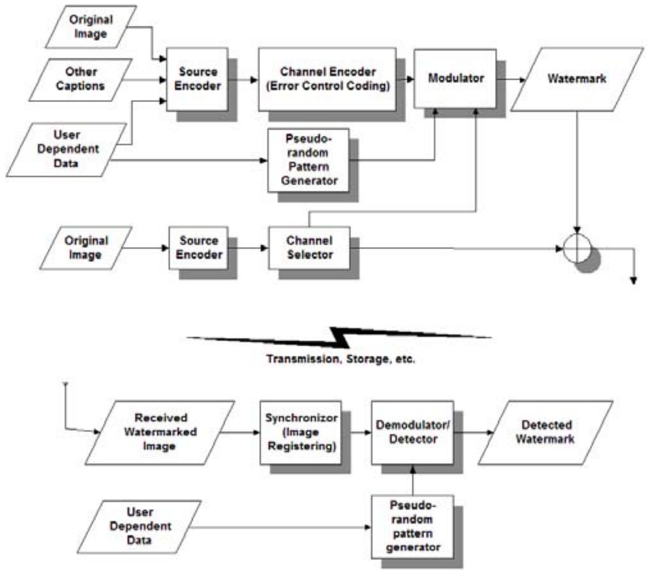


Fig. 1. Communication system model for watermarking problems.

Therefore, we can adopt concepts from the digital communication system to analyze the digital image watermarking problem.

Prior work on digital watermarking has mainly focused on realizations of the techniques. Only a few focused on theoretical analysis. Among then, [6] used game theory to explain watermarking problems; [7] used statistical invisibility to explain the robustness of watermarking algorithms. Given specific scenarios and constraints, [8] [9] [10] [11] [12] used communication theory to explain watermarking problems.

A. Channel capacity of the original image

Definition 1: Consider the original image $\mathbf{X}$ as a discrete-time random process $(X_1\ X_2\ \cdots X_N)^T$, and the watermark $\mathbf{W}$ as also a discrete-time random process $(W_i,\ 1 \leq i \leq N)$. Therefore, a watermarked image $\mathbf{Y}$ is $X_i + W_i,\ 1 \leq i \leq N$. A watermarked image $\mathbf{R}$ after some image manipulations $\mathbf{T}$ becomes

$$R_i = f(X_i + W_i) = X_i + W_i + T_i, \quad 1 \leq i \leq N \quad (1)$$

The last equal sign is a linear approximation to function $f(.)$.

The sufficient statistics for detection is $< R_i, W_i >$.

$$< R_i, W_i > = < X_i, W_i > + < W_i, W_i > + < T_i, W_i > \quad (2)$$

According to the equation above, a private watermark detection scheme without projection of the original image, $< X_i, W_i >$, has smaller noise value. Therefore, its probability of error is smaller.

As mentioned in Section I, the three digital image watermarking criteria, *maximal capacity*, *robustness*, and *imperceptibility*, are trade-off's. In this subsection, we define these three terms based on *channel capacity*. Note that in Section II-B, we will define these three terms based on *error rate*.

Definition 2 (Maximal Capacity): The maximal capacity is bounded by the "channel capacity" of the original image.

Definition 3 (Robustness): According to Shannon's channel coding theorem [13], reliable communication is achieved if the transmission rate is lower than the channel capacity.

$$R < C \Rightarrow \text{reliable communication}$$

Therefore, successful watermark detection is guaranteed if the total bits embedded in an original image is smaller than the channel capacity calculated.

Definition 4 (Imperceptibility): Imperceptibility is achieved by

1) Low SNR (Signal to Noise Ratio) $\frac{\gamma^2}{\sigma^2}$, where "signal" refers to the watermark and "noise" refers to the original image. See equations (3) and (7) for the definition of σ^2 and γ^2.
2) High correlation between the watermark and the original image $\frac{Cov(W_i,X_i)}{\sqrt{Var(W_i)\,Var(X_i)}}$.

1) Memoryless channel and source model: First we consider the original image and watermark as memoryless channel and source. This could be done after properly source coding of the original image. Take Karhunen-Loève transform for example. It can turn the image into N independent channels (or dimensions). The number, N, is image dependent. The channel capacity $C \overset{\text{def}}{=} \max_{p(\mathbf{W})} I(\mathbf{W};\mathbf{R})$ is then calculated. Assume this is a Gaussian channel which has the lowest channel capacity among all.

$$X_i \sim N(0, \sigma_i^2), \quad 1 \leq i \leq N \quad (3)$$

The watermark power is constrained by the human visual perceptibility to have a total power S.

$$\sum_{i=1}^{N} E[W_i^2] \leq S \quad (4)$$

Then,

$$C(S) = \sum_{i=1}^{N} \frac{1}{2} \log_2 (1 + \frac{\gamma_i^2}{\sigma_i^2}) \quad (5)$$

where

$$\gamma_i^2 = \max[0, \theta - \sigma_i^2] \quad (6)$$

$$\sum_{i=1}^{N} \gamma_i^2 = S \quad (7)$$

θ is chosen such that (7) holds, and is where we bring in Langrange multiplier. If we take T_i into account, T_i along with X_i are noises to W_i. The corresponding noise power σ_i^2 is replaced by $\sigma_i'^2$.

$$\begin{aligned} Noise &= X_i + T_i & (8) \\ \sigma_i'^2 &= \sigma_i^2 + \sigma_{T_i}^2 + 2Cov(X_i, T_i) & (9) \end{aligned}$$

$$C(S) \simeq \sum_{i=1}^{N} \frac{1}{2} \log_2 (1 + \frac{\gamma_i^2}{\sigma_i^2 + \sigma_{T_i}^2 + 2Cov(X_i, T_i)}) \quad (10)$$

Compare (10) with (5), with manipulation considered, the channel capacity decreases. In addition to the original noise power σ_i^2, noise power introduced by manipulations $\sigma_{T_i}^2$ and covariance between X_i and T_i contributes to the total noise power $\sigma_i'^2$.

$$
\begin{aligned}
\sigma_i'^2 &\overset{usually}{<} \sigma_i^2 + \sigma_{T_i}^2 + 2\sigma_i^2 && (11)\\
&= 3\sigma_i^2 + \sigma_{T_i}^2 && (12)\\
&\simeq 3\sigma_i^2 && (13)\\
C(S) &\simeq \sum_{i=1}^{N} \frac{1}{2}\log_2(1+\frac{\gamma_i^2}{3\sigma_i^2}) && (14)
\end{aligned}
$$

If $\sigma_i^2 = \sigma^2$ for all i, we can simplify (5), (6), and (7).

$$C(S) = \frac{N}{2}\log_2(1+\frac{\gamma^2}{\sigma^2}) \qquad (15)$$

$$\gamma^2 = \frac{S}{N} \qquad (16)$$

Since $\gamma^2 \ll \sigma^2$, we further simplify the equation,

$$C(S) \simeq \frac{N}{2}(\log_2 e)(\frac{\gamma^2}{\sigma^2}) \qquad (17)$$

Take T_i into account and apply result obtained in (13).

$$C(S) \simeq \frac{N}{2}(\log_2 e)(\frac{\gamma^2}{3\sigma^2}) \qquad (18)$$

Some important results derived from the above derivations are worth discussing. First, from (5), (10), (14), (15) and (18), the larger the watermark power, the greater the capacity value. While greater watermark power implies weaker imperceptibility (Definition 4), this means capacity and imperceptibility conflict. The later two equations (15) and (18), although a simplified version, clearly show us the trade-off between imperceptibility and capacity.

Next, as mentioned in Definition 4, the second criteria judging if a watermark inserted is imperceptible is the correlation between the watermark and the original. Therefore, the watermark is designed to maximize the the correlation. In (3), we assume the original image as a Gaussian channel. The correlation is maximized if the watermark signal is also Gaussian. This explains why [3] choose Gaussian signal as a watermark.

2) Markov channel and source model: Consider a Markov–n channel. Let $Q(\mathbf{y}|\mathbf{x}) = Q(y_1,\cdots,y_n|x_1,\cdots,x_n)$ be the probability of block output $(y_1,\cdots,y_n)$, given block input $(x_1,\cdots,x_n)$, of a discrete–time stationary channel. Then the capacity of this channel is

$$C(S) = \lim_{n\to\infty}\frac{1}{n}C_n(nS) \qquad (19)$$

where C_n is the capacity cost function on a block of length n, and

$$
\begin{aligned}
C_n(S(\theta)) &= n^{-1}\sum_{i=1}^{n}\max[0,\frac{1}{2}\log_2(1+\frac{\gamma_i^2}{\sigma_i^2})] && (20)\\
&= n^{-1}\sum_{i=1}^{n}\max[0,\frac{1}{2}\log_2(1+\frac{\theta}{\sigma_i^2})] && (21)\\
S(\theta) &= \sum_{i=1}^{n}\max[0,\theta-\sigma_i^2] && (22)
\end{aligned}
$$

Take the limit, (19) gives

$$
\begin{aligned}
C(S_\theta) &= \frac{1}{2}\int_{-\frac{1}{2}}^{\frac{1}{2}}\max[0,\log_2\frac{\theta}{N(f)}]\,df && (23)\\
S_\theta &= \int_{-\frac{1}{2}}^{\frac{1}{2}}\max[0,\theta-N(f)]\,df && (24)
\end{aligned}
$$

where $N(f)$ is the noise power spectral density.

$$N(f) = \sum_{k=-\infty}^{\infty}\phi_k \exp^{-j2\pi kf} \qquad (25)$$

and ϕ_k is the noise autocorrelation function. Refer to [13] for details.

The relation between capacity and watermark power is not explicitly shown in (23) as in Section II-A1. The relation is still the same, the larger the watermark power, the greater the capacity value. Since the channel and source is not memoryless, noise in one index k will propagate to others. Thus, instead of using single term σ_i^2 and summing all i's, $N(f)$ is used and integral is taken.

B. Error rate of the watermark detector

In this subsection, we define *capacity*, *robustness*, and *imperceptibility* in a different way.

Definition 5 (Capacity): After source coding in Fig. 1, if the watermark codeword set has $M = 2^k$ codewords, then its capacity is M.

Definition 6 (Robustness): Probability of error P_e is defined to be the measure of robustness.

Definition 7 (Imperceptibility): Similar to Definition 4, imperceptibility is achieved by larger value of the "jamming margin", $\frac{J_{av}}{P_{av}}$, where J_{av} refers to the average power of the original image and P_{av} refers to the average power of the watermark signal.

From [14], the probability of error of a detector of a communication system in Fig. 1 is union bounded as

$$
\begin{aligned}
P_e &\leq \sum_{m=2}^{M} Q\left(\sqrt{\frac{(\frac{2W}{R})}{(\frac{J_{av}}{P_{av}})}R_cW_m}\right) && (26)\\
&\leq (M-1)Q\left(\sqrt{\frac{(\frac{2W}{R})}{(\frac{J_{av}}{P_{av}})}R_cW_m}\right) && (27)
\end{aligned}
$$

for the Direct Sequence Spread Spectrum (DSSS) system. Where $\frac{W}{R}$ is the *"processing gain"* resulting from spread spectrum communication.

$$\frac{W}{R} = \frac{T_b}{T_c} = \frac{\text{data interval}}{\text{chip interval}} \qquad (28)$$

and R_cW_m is the *"coding gain"* resulting from error correction coding.

$$
\begin{aligned}
R_c &= \frac{k}{n} && (29)\\
W_m &= \min_{\text{Codeword Set}} \text{weight} && (30)
\end{aligned}
$$

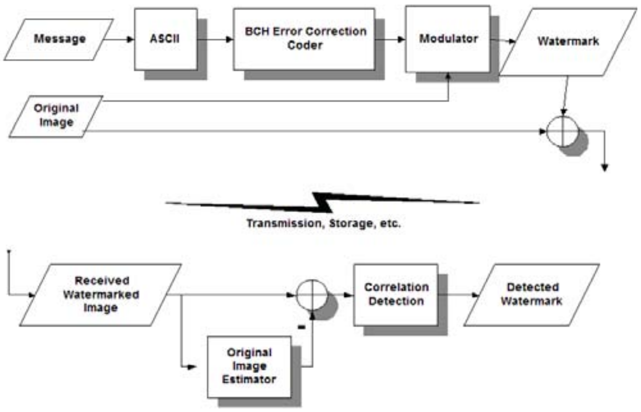


Fig. 2. Proposed DSSS watermarking system.

Note that $Q(.)$ is monotone decreasing function.

$$Q(x)=\frac{1}{\sqrt{2\pi}}\int_{x}^{\infty}\exp^{-\frac{t^2}{2}}\,dt,\ \ x\geq 0 \tag{31}$$

From (26) and (27) above, the relations among probability of error, capacity, processing gain, jamming margin, and coding gain are clear. With other control variables fixed,

- Capacity ↑ ⇒ Probability of error ↑. More errors occurs as more bits are embedded in an image.
- Processing gain ↑ ⇒ Probability of error ↓. The broader the spread spectrum codes spread, the smaller the error rate.
- Jamming margin ↑ ⇒ Probability of error ↑. Increasing the watermark power reduces the error rate. In this case, watermark is more visible.
- Coding gain ↑ ⇒ Probability of error ↓. The introduction of error correction codes reduces the probability of error.

III. PROPOSED WATERMARKING SYSTEM

We assume human visual system in spatial domain is proportional to the image gradient information. By calculating the image gradient, we can determine the theoretical bound of channel capacity of an image provided the noise power is known. In our approach, we quantize all capacities into 5 bins. Every bin has different coding rates. We then apply DSSS (Direct Sequence Spread Spectrum) technique to spread the message.

The DSSS watermarking system is depicted in Fig. 2. The watermark embedding steps are as follows:

1) Load text message of length of 8 bytes.
2) Transform the text to binary string by ASCII.
3) Encode the ASCII codes by BCH(511, 10) codes. The BCH (Bose-Chaudhuri-Hocquenghem) code is one in the linear block code family.
4) Modulate the BCH-coded binary string with the original image.
5) Add the watermark to the original image.

The watermark detection includes the following steps:

1) Estimate the original image. If the original image is ready at hand, substitute the real original image for the estimated original image.
2) Subtract the estimated original image from the received watermarked image.
3) Normalize the received watermark from the previous step by image gradient of the estimated original image. Compute the correlation of the normalized received watermark with the possible candidates of BCH-coded 8-byte text. The detected watermark is the candidate with the largest correlation value with the normalized received watermark.

The modulation of watermark with the original image is performed as follows:

1) Compute the original image gradient.
2) Adaptive to image manipulations considered, select locations with largest capacity values. Let $SWPF$ be spatial watermark power factor, $IMNP$ be image manipulation noise power, and QN be quantization noise, respectively. Capacity is computed followed the following equation.

$$C=\frac{1}{2}\log_2\left(\frac{SWPF\times\text{gradient}}{IMNP+QN}\right) \tag{32}$$

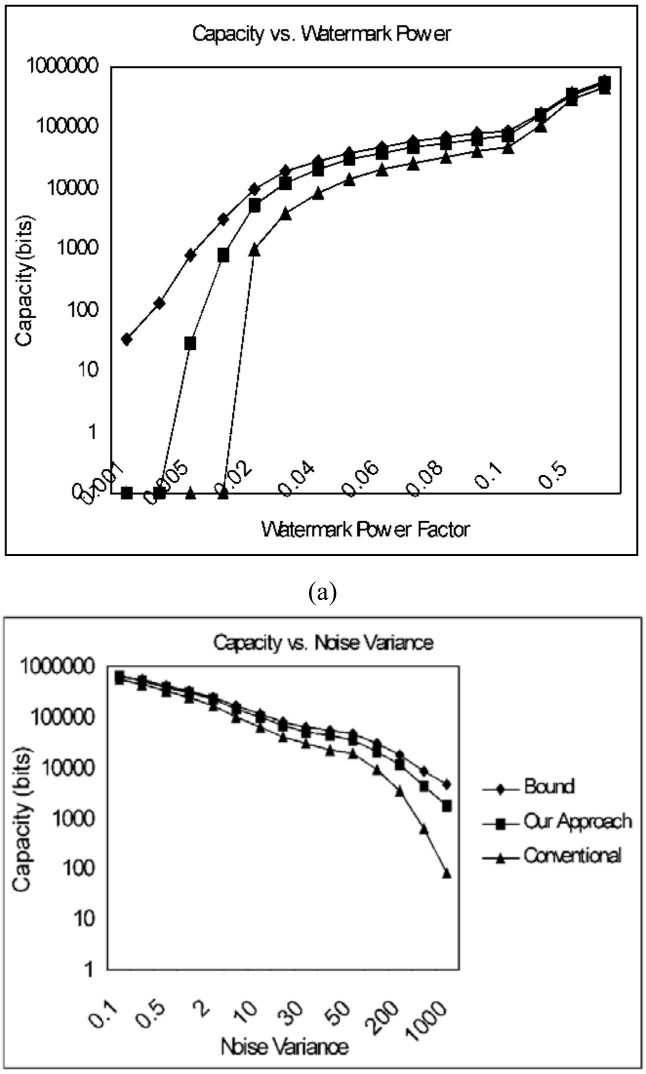
   If several image manipulations are considered, sum all capacity values in each location. Then select locations with the largest sum values.
3) Mark locations selected to embed watermark with 1 and leave the others -1. The resulted binary matrix is called location matrix.
4) Location matrix times with the multiplication of spatial watermark power factor and gradient. The resulted matrix is called gradient mask.
5) Gradient mask then times with the BCH-coded string to get the watermark.

In conventional approach, only channel with capacity greater than one is adopted to be put in the watermark. Therefore, the total amount of bits embedded in our scheme is better than the conventional one. See Figs. 3(a) and 3(b) for results. The well-known Cox's approach [3] embeds only 1000 bits of information in an image of the same size as our test image.

Six images shown in Fig. 4 are used for experimentation. All are of size 512×512 and in "bmp" file format. Here in the following, we make a brief description of each image. (a) Lena: A well-known image. (b) Mandrill: This image has complex texture. (c) Monet: Monet's "Japanese Bridge and Lilly Pond." (d) Balloons: "CMYK Balloons" in sample images of Adobe PhotoShop 5.0. It has large smooth area, sky, as well as complex area, crowd in the bottom. (e) Spine: "Spine" in sample images of Matlab 5.1. It is a simple medical image. (f) Text: Text image is scanned by a 600 dpi scanner.

The computed channel capacities with respect to different images are shown in Fig. 5. As a result, we found that channel capacity increases with stronger watermark power and decreases with stronger noise power.

In the watermark detection stage, a correlation detector is used to decode the watermark message. Since this is a spread-spectrum based technique, a key is required to retrieve the watermark message.



(a)

(b)

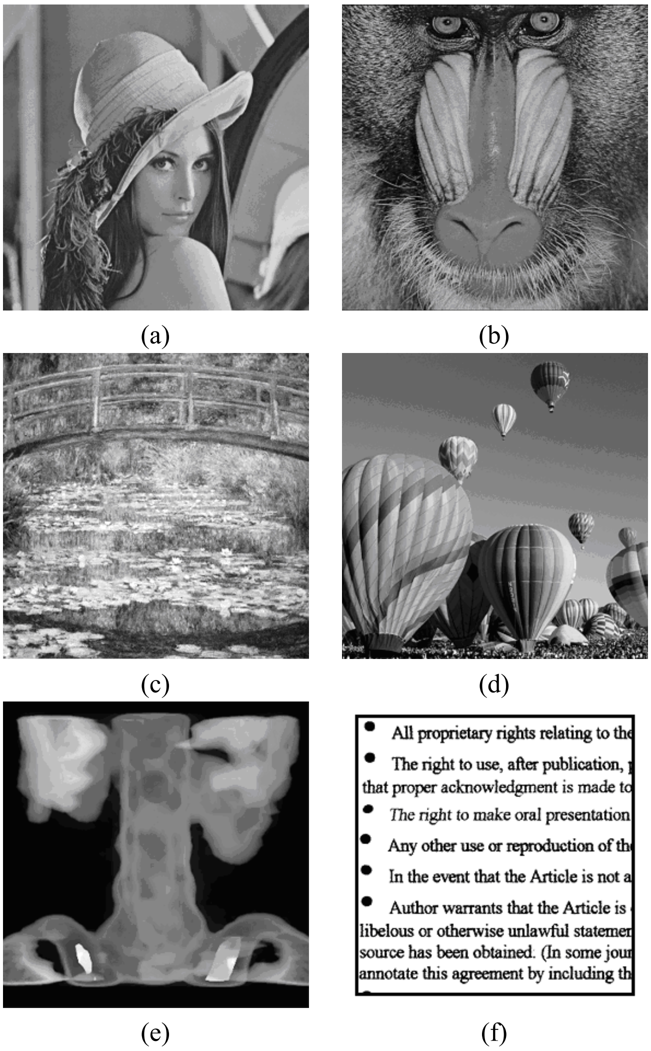
Fig. 3. (a) Greater watermark power can hide more messages. (b) Worse channel condition (larger noise variance) reduces capacity.

IV. CONCLUSION

In Section II, we conclude from the derivations that the larger the watermark power, the greater the capacity value. In addition, capacity and robustness conflict since a robuster system can tolerate greater noise power. The experiment results in Figs. 3(a) and 3(b) follow the derivation results.

In this paper, we apply knowledge from the digital communication theory to analyze a general watermarking problem. We can know the characteristics and inherent limitations of a watermarking technique from a structural point of view. We can also foresee the future trend of watermarking researches.

Brief experiments are conducted in this paper to prove our analyses. More test images and more comparisons between ours and other watermarking techniques are required in the future. The noise we study here is the simplest independent Gaussian noise. We hope to see a more comprehensive analysis of image watermarking techniques and better improvements in the near future.


(a) (b)

(c) (d)

(e) (f)

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Fig. 4. Six test images: (a) Lena, (b) Mandrill, (c) Monet, (d) Balloons, (e) Spine and (f) Text.

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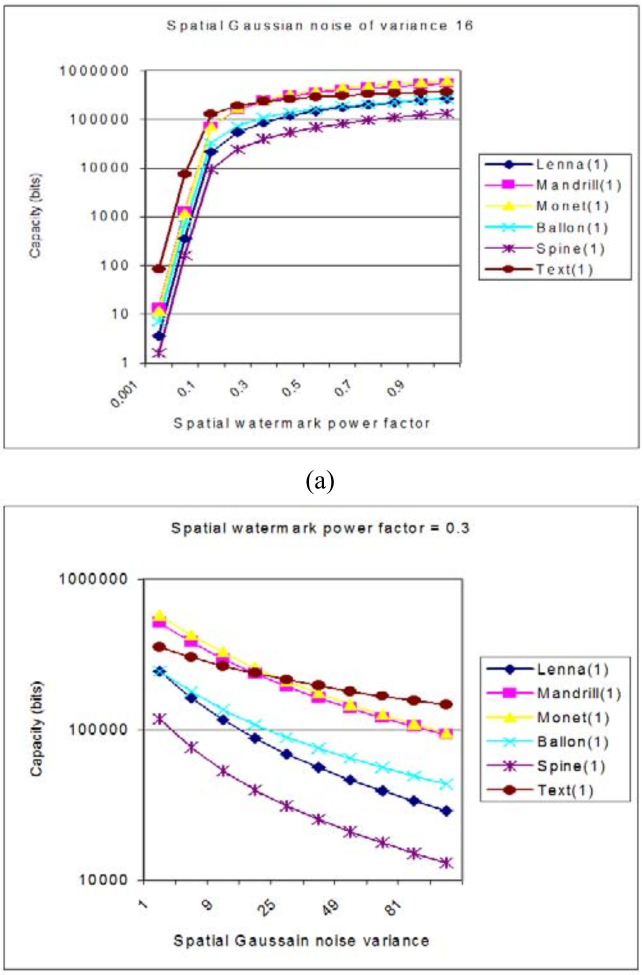

(a)

(b)

Fig. 5. Channel capacity of different test images: (a) Channel capacity vs. watermark power, and (b) Channel capacity vs. noise variance.

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