Image Barcodes

Niranjan Damera-Venkata and Jonathan Yen
Hewlett-Packard Laboratories, Palo Alto CA

ABSTRACT

A Visually significant two-dimensional barcode (VSB) developed by Shaked et. al. is a method used to design an information carrying two-dimensional barcode, which has the appearance of a given graphical entity such as a company logo. The encoding and decoding of information using the VSB, uses a base image with very few graylevels (typically only two). This typically requires the image histogram to be bi-modal. For continuous-tone images such as digital photographs of individuals, the representation of tone or "shades of gray" is not only important to obtain a pleasing rendition of the face, but in most cases, the VSB renders these images unrecognizable due to its inability to represent true gray-tone variations. This paper extends the concept of a VSB to an image bar code (IBC). We enable the encoding and subsequent decoding of information embedded in the hardcopy version of continuous-tone base-images such as those acquired with a digital camera. The encoding-decoding process is modeled by robust data transmission through a noisy print-scan channel that is explicitly modeled. The IBC supports a high information capacity that differentiates it from common hardcopy watermarks. The reason for the improved image quality over the VSB is a joint encoding/halftoning strategy based on a modified version of block error diffusion. Encoder stability, image quality vs. information capacity tradeoffs and decoding issues with and without explicit knowledge of the base-image are discussed.

Keywords: information embedding, hardcopy security, barcodes

1. INTRODUCTION

This paper deals with information embedding in hardcopy. The objective is to be able to encode information into a continuous-tone base-image, which is then printed using a conventional inkjet or laserjet printer. The printed image is scanned via a scanner and the resulting digital image is processed by a decoder to recover the transmitted message. The decoder may or may not have access to the original base-image. We refer to the hardcopy image with information embedded in it as an image barcode (IBC) . The information capacity of an image barcode lies between conventional 2-D barcode technologies such as PDF-117 and hardcopy watermarks. In a typical application for example, we could embed the entire biography of an individual onto the photograph on his/her bussiness card. Further, small mp3 clips and executables may also be embedded into hardcopy images providing a rich media experience.

Our image communication system uses several components of the visually significant barcode technology developed by Shaked et. al.[1] The VSB technology is a sophisticated image processing pipeline to enable efficient hardcopy information encoding on bi-level base images, such as company logo images. We make use of the print-scan channel model developed by Shaked et. al. for visually significant barcodes (VSB). A VSB encodes information onto a bi-level base image by block-based XOR modulation. This is illustrated in Fig. 1. Photographic images however, are continuous tone and the VSB technology is not directly applicable. However if the continuous tone image is then halftoned an intermediate binary image results, on which VSB encoding may be attempted. This approach to generating a barcode representation of a grayscale input image is illustrated in Fig. 2. Typical haftoning methods such as screening or error diffusion could be employed to convert a grayscale image into an intermediate binary halftone image. Fig. 4(a)-(c) shows example encoded images, that use various halftoning methods to produce an intermediate halftone from a grayscale base-image. VSB encoding is then performed on the intermediate halftones. It is observed that encoding information by using the intermediate binary halftone image as a base-image produces poor results even when high-quality halftoning algorithms such

Further author information: (Send correspondence to N. Damera-Venkata.)
N. Damera-Venkata.: E-mail: damera@exch.hpl.hp.com, Telephone: 1 650 857 4788
Address: Hewlett-Packard Laboratories, 1501 Page Mill road, Palo Alto, CA 94304

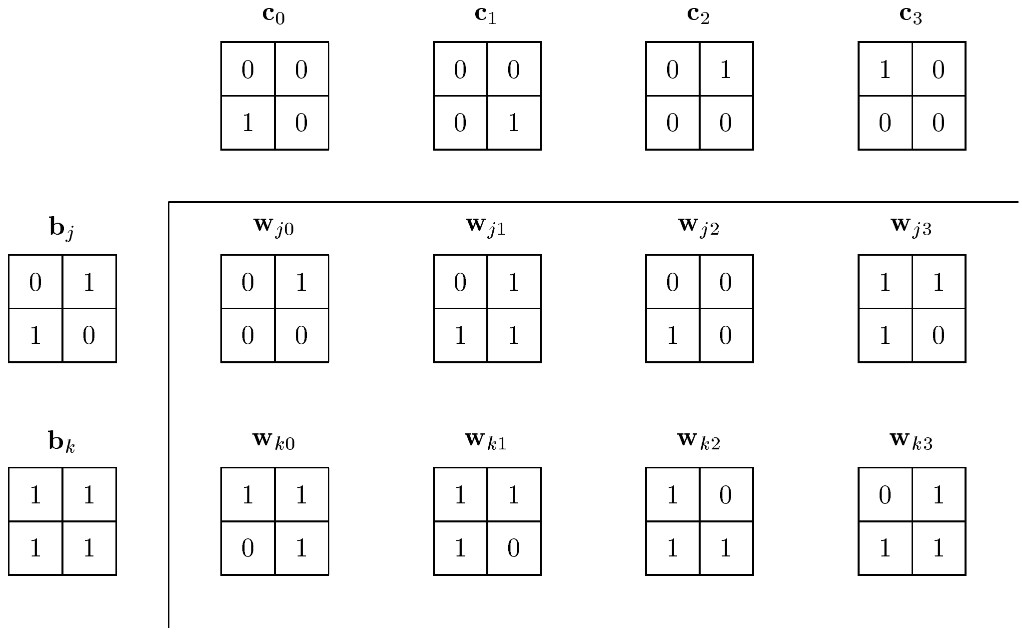

Figure 1. Example XOR modulation encoding used in the Visually Significant Barcode (VSB) technology. The encoded block $\mathbf{w}$ is the result of an XOR operation between the encoding codeword block $\mathbf{c}$ and the bi-level base-image block $\mathbf{b}$. Thus $\mathbf{w}_{lm} = \mathbf{c}_m \otimes \mathbf{b}_l$. Only two of the 2^4 possible base-image blocks are shown.

Figure 2. Encoding continuous-tone images by generating an intermediate bi-level halftone and then using VSB encoding. The halftoning stage does not use knowledge of the encoding process.

as error diffusion are used to produce the intermediate halftone. This is because the subsequent XOR modulation based encoding disturbs the pixel distribution in the intermediate halftone, resulting in a poor quality encoded image. Since our objective is to optimize overall encoded image quality, the approach we take with image barcodes is to jointly encode and halftone based on the message symbols to optimize encoded image quality. This process is illustrated in Fig. 3 Thus the halftoning stage has knowledge of the encoding stage and vice versa. Thus the IBC is an extension of the VSB technology to handle continuous tone input images. Fig. 4(d) shows an example image barcode.

An IBC is able to represent tone-variations in a given grayscale base-image, while at the same time embedding a lot of information. This is achieved by a modified version of block error diffusion,[2] modified to support joint encoding/halftoning. First an intermediate binary halftone image is generated which is dependent on the codewords as well as the base image. The output is encoded as a VSB on the resulting intermediate binary halftone image. Also the quantization errors due to the encoding are diffused to future blocks using block error diffusion. In this manner, both halftoning and encoding can be performed jointly.

The IBC may be decoded from a scanned version of the printed image. When we know the grayscale base-image at the decoder, we will show how we can use this information to decode the message signal using maximum-likelihood VSB decoding. Even when the base image is not known decoding is possible since under certain conditions we may estimate the intermediate binary halftone directly from the observed data and use it to decode the message signal. We also discuss the stability of our proposed joint encoding halftoning strategy

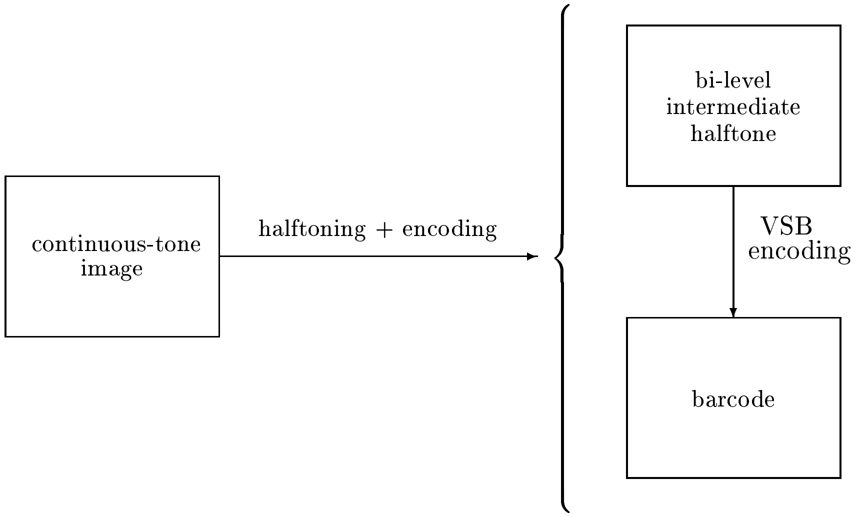

Figure 3. Joint encoding and halftoning of a continuous-tone image to produce an image barcode (IBC). The halftoning stage uses knowledge of the encoding process to improve overall encoded image quality. The encoded halftone is still a VSB with the intermediate halftone regarded as the base bi-level image.

and show how image quality may be traded for increased capacity.

Section 2 reviews the VSB technology. Since we use many features of the VSB in our image barcode system, we emphasize aspects of the VSB that are common to the IBC. Section 3 introduces the joint halftoning/encoding strategy used to encode information into an image barcode. We show that the proposed algorithm is able to represent any continuous tone variation in a stable manner and is able to trade image quality for increased capacity. Section 4 discusses how a scanned image barcode may be decoded when the original grayscale base image is either explicitly known at the decoder or is unknown at the decoder. We refer to the former case as guided decoding and the latter case as blind decoding. Finally Section 5 summarizes the contributions of the paper.

2. VISUALLY SIGNIFICANT BARCODES

A detailed description of the VSB technology is provoded in.[1] Here we provide an overview of VSBs for completeness. The VSB encoder first partitions the bi-level base-image into blocks. At each block location a symbol is selected from a codebook and the output is computed by performing an XOR operation between the input block and message symbol block. This operation is illustrated in Fig. 1. If 2×2 blocks are used to encode 4 different codewords, then 2 bits are encoded per base image block. However to ensure robust transmission the codeword bitstream is mapped to a more redundant bitstream using error correcting codes. For example if a $16 \rightarrow 31$ BCH code were used, the actual information capacity per block is halved. Fiducial marks are inserted at the corners to help the decoder in alignment. Fig. 1 shows that the XOR encoding using two different codewords on two different base-image blocks can produce the same output encoded image block. Thus the bi-level base-image must be known or estimated if we were to estimate the message symbols from the output halftone symbols. If the target VSB print resolution is 100 dpi and the printer has a native resolution of 600 dpi, each encoded halftone pixel is replaced by a 6×6 block by pixel replication before printing.

The VSB decoder operates on a scanned version of the encoded hardcopy image. Let us assume that the scanning resolution is 600 dpi. Then an observed 6×6 block corresponds to one encoded halftone pixel. The decoder first identifies fiducial marks to enable the decoder to compensate for global geometric distortions such as global translation, rotation and skew due the the print scan process. This step involves corner detection, estimation and application of a global geometric transform followed by bilinear interpolation. The result of this step is a rectangular image. Before the visually significant barcode may be decoded using maximum likelihood detection theory, the halftone dots in the encoded image must be matched up with corresponding grayscale observations in the scanned image. The VSB accounts for local space deformations arising due to the fact that dots corresponding to certain co-ordinates in the original image are located at different points in the copy. Most deformations were observed to be approximately separable, i.e: a dot expected at $(x_0, \cdot)$ is located at location

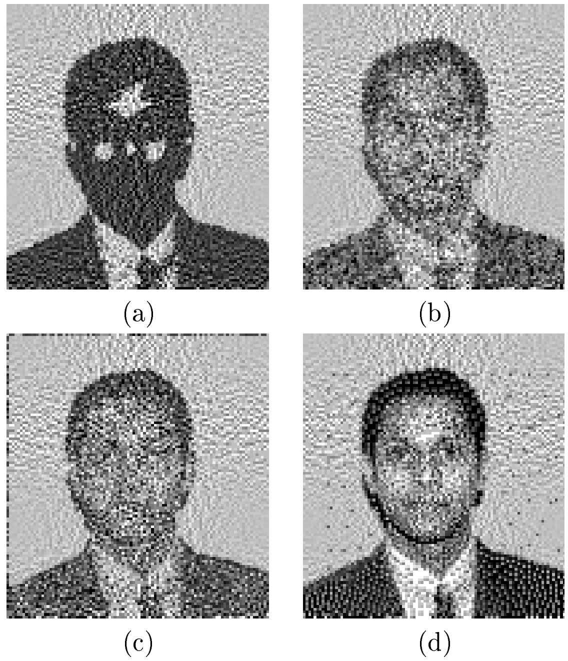

Figure 4. Barcodes generated from various intermediate halftones. (a) Intemediate halftone generated via thresholding. (b) Intermediate halftone generated by Floyd-Steinberg error diffusion. (c) Intermediate halftone generated by Levien's green noise error diffusion.[3] (d) Intermediate halftone generated by proposed joint encoding/halftoning strategy. The actual rendering resolution is 150 dpi. The images may be viewed from a distance to simulate typical viewing.

$(x_0 + \Delta_x, \cdot)$, and similarly a dot expected at $(\cdot, y_0)$ is located at location $(\cdot, y_0 + \Delta_y)$. Row and column interfaces are aligned with pixel rows and columns, and the deformation is expressed only in their uneven distribution. The sum of absolute values of horizontal gradients in columns is used to determine the interface at columns (from peaks in the gradient sum).A similar procedure is used to find row interfaces. Dots are then virtually aligned by augmenting the scanned image with a list (describing a a potentially non-uniform grid) of dot centers.

Once the scanned barcode has been aligned with the encoded halftone, there is a correspondence between a measurement patch and an encoded halftone pixel. A linear discriminant y is formed by multiplying the elements of the patch pointwise by a truncated Gaussian and summing. This reduces the dimensionality of the observations per encoded halftone pixel to unity. From an empirical analysis of the shape of the discriminant histogram for several inkjet and laserjet printers Shaked et. al.[1] propose the following asymmetric Laplacian probability model for the observations

$$P(y|0) = \begin{cases} \alpha_{0L} e^{-\alpha_{0L}(\mu_0 - y)} & y < \mu_0 \\ \alpha_{0R} e^{-\alpha_{0R}(\mu_0 - y)} & y > \mu_0 \end{cases} \tag{1}$$

$$P(y|1) = \begin{cases} \alpha_{1L} e^{-\alpha_{1L}(\mu_1 - y)} & y < \mu_0 \\ \alpha_{1R} e^{-\alpha_{1R}(\mu_1 - y)} & y > \mu_0 \end{cases} \tag{2}$$

For each individual image the parameters $\{\alpha_{0L}, \alpha_{0R}, \alpha_{1L}, \alpha_{1R}, \mu_0, \mu_1\}$ are different and are estimated using an expectation maximization (E-M) approach.[1] Once the parameters are estimated, a likelihood score is computed for each possible message symbol. Thus the decoded codeword at location $\mathbf{m}$ is given by

$$\hat{\mathbf{c}}(\mathbf{m}) = \underset{\{\mathbf{c} \in \mathcal{C} : \mathbf{w} = \mathbf{b}(\mathbf{m}) \otimes \mathbf{c}\}}{\arg\max} \prod_{i=0}^{N^2-1} P(y_i | w_i) \tag{3}$$

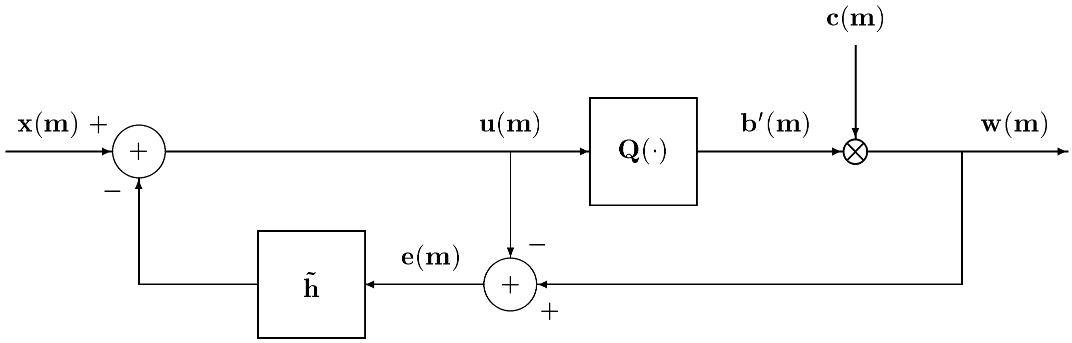

Figure 5. System block diagram for the image barcode encoder. $\tilde{\mathbf{h}}$ represents a fixed 2-D nonseparable FIR error filter with matrix valued coefficients. $\mathbf{Q}$ denotes the block quantizer. The encoded image block $\mathbf{w}(\mathbf{m})$ is obtained by modulating the codeword $\mathbf{c}(\mathbf{m})$ onto the intermediate halftone block $\mathbf{b}'(\mathbf{m})$ using the XOR operation denoted by $\otimes$. The vector $\mathbf{m}$ represents the 2-D index (m_1, m_2).

where $\mathbf{b}(\mathbf{m})$ represents the known bi-level base image block at location $\mathbf{m}$ and $\mathbf{c}$ represents a possible codeword block. $w_i \in \{0, 1\}$ represents the encoded halftone value expected at location i if codeword $\mathbf{c}$ was used to encode the current base-image block $\mathbf{b}(\mathbf{m})$. $\otimes$ denotes the XOR operation.

3. ENCODING INFORMATION INTO AN IMAGE BARCODE

This section shows how message symbols may be embedded into image barcodes by joint information embedding and halftoning. Section 3.1 describes the basic operation of the image barcode encoder. Section 3.2 discusses the stability of the encoding process and introduces the concept of fictitious codewords to ensure that all graylevels can be reproduced without encoder instability. Section 3.3 shows how the fictitious codewords could be used to trade off barcode quality for information capacity.

3.1. Image Barcode Encoder

Fig. 5 shows the system block diagram for the encoding of information into an image barcode.

We generate an IBC of a continuous-tone base image X (which may be a grayscale image having several graylevels) by jointly manipulating the base image X into a bi-level image B', and an encoded image W (based on the message bits), such that application of a VSB on B' yields W. Constraints on B' may be enforced in the joint encoding process to allow B' to be estimated from W alone, using the methods described in Section 4.2. Once B' is determined from W, it plays the role of the base-image in a regular VSB, and the encoded IBC may be decoded as if it were a regular VSB.

1. The original image is divided into blocks. The blocks need not be rectangular , but must tile to cover the whole image. This is identical to the first step of VSB encoding.[1]

2. The processing of the blocks usually proceeds in raster or serpentine scan order. At each block a decision is made to represent that block with a block selected from finite number of possible blocks (composed of binary levels) of the same size. One example for possible allowed blocks is a block with all pixels equal to 1 (white) and another with all pixels equal to 0 (black). These blocks make up the intermediate halftone image B'. The decision to allow a black block or a white block in the intermediate halftone is made by simply thresholding the average modified input block value (modified by past errors).

3. The current message code word is modulated onto the binary block using XOR modulation, just as with a regular VSB. The modulated blocks make up the encoded image W. Fig. 6 shows codeword alphabet $C = \{[0\ 0\ 0\ 1]^T, [0\ 0\ 1\ 0]^T, [0\ 1\ 0\ 0]^T, [1\ 0\ 0\ 0]^T\}$ used to encode 2×2 intermediate halftone blocks. The codewords are represented as row ordered vectors.

4. The quantization error between the modulated binary result and the current graylevel block is diffused to neighbouring unprocessed graylevel blocks using a block error filter[2] with a diffusion matrix $D = 0.25\,\mathbf{1}_{4\times4}$ which corresponds to diffusing the average block error to neighboring unprocessed pixel blocks.

5. The next graylevel block in the scan path is considered and steps 2)-5) are repeated until all image pixel blocks have been processed.

Consider the case when pixel-blocks are quantized by allowing only solid black or solid white blocks in the intermediate halftone image B'. This means that the resulting ecoded block due to modulating the message onto an intermediate halftone pixel-block, is always equal to the given codeword or its compliment. Fig. 6 shows the possible encoded image blocks in this case. Since the codewords in a VSB are generated by toggling very few pixels (usually just one or two) of a uniform white or black block, the encoded pixel-blocks of E are reproduced from B' with a change of just one or two pixels being corrupted due to the message. This yields overall robustness. The following equations describe the image barcode encoding process using 2×2 block encoding.

The quantizer $\mathbf{Q}(\cdot)$ converts the modified input block $\mathbf{u}(\mathbf{m})$ into the intermediate halftone block $\mathbf{b}'(\mathbf{m})$.

$$\mathbf{b}'(\mathbf{m}) = \mathbf{Q}(\mathbf{u}(\mathbf{m})) = \begin{cases} [1\;1\;1\;1\,]^T & \sum_{i=0}^{3} u_i(\mathbf{m}) > \frac{1}{2} \\ [0\;0\;0\;0\,]^T & else \end{cases} \tag{4}$$

The codeword $\mathbf{c}(\mathbf{m})$ is modulated onto the intermediate halftone using XOR modulation encoding.

$$\mathbf{e}(\mathbf{m}) = \mathbf{c}(\mathbf{m}) \otimes \mathbf{b}'(\mathbf{m}) \tag{5}$$

The resulting quantization error block $\mathbf{e}(\mathbf{m})$ is diffused using a block error filter $\tilde{\mathbf{h}}$ with matrix valued coefficients.

$$\left[\tilde{\mathbf{h}} \star \mathbf{e}\right](\mathbf{m}) = \sum_{\mathbf{k}\in\mathcal{S}_+} \tilde{\mathbf{h}}(\mathbf{k})\mathbf{e}(\mathbf{m}-\mathbf{k}) \tag{6}$$

Here the error filter is assumed to have a causal support $\mathcal{S}_+$ with $(0,0) \notin \mathcal{S}_+$. We will assume a the Floyd-Steinberg filter[4] support set $\mathcal{S}_+ = \{(0,1),(1,1),(1,0),(1,-1)\}$. The modified input is computed by subtracting the feedback signal from the input signal.

$$\mathbf{u}(\mathbf{m}) = \mathbf{x}(\mathbf{m}) - \left[\tilde{\mathbf{h}} \star \mathbf{e}\right](\mathbf{m}) \tag{7}$$

We use the block error filter with coefficients

$$\begin{aligned} \tilde{\mathbf{h}}(0,1) &= \frac{7}{64}\mathbf{1}_{4\times4} \\ \tilde{\mathbf{h}}(1,1) &= \frac{1}{64}\mathbf{1}_{4\times4} \\ \tilde{\mathbf{h}}(1,0) &= \frac{5}{64}\mathbf{1}_{4\times4} \\ \tilde{\mathbf{h}}(1,-1) &= \frac{3}{64}\mathbf{1}_{4\times4} \end{aligned}$$

This corresponds to diffusing the average error using the Floyd-Steinberg weights and distributing the error diffused to a pixel-block equally to all elements within the pixel-block.

3.2. Stabilizing the Image Barcode Encoder

Since the encoding stage modifies the thresholding process in block error diffusion based on the message signal, it is possible that the resulting error might become unbounded resulting in unstable encoder behavior and degradation in image quality. We see that for 2×2 blocks, with the IBC encoder using the codewords given in Fig. 6 the following stability result holds.

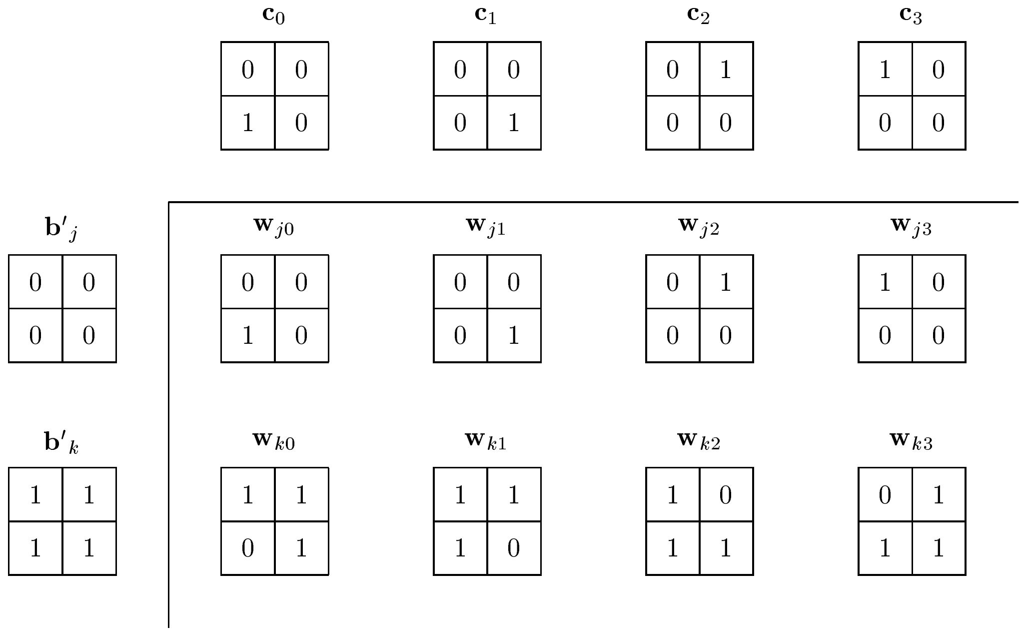

Figure 6. Example XOR modulation encoding used in Image the Barcode (IBC) technology. The encoded block $\mathbf{w}$ is the result of an XOR operation between the encoding codeword block $\mathbf{c}$ and the bi-level intermediate halftone block $\mathbf{b}'$. Thus $\mathbf{w}_{lm} = \mathbf{c}_m \otimes \mathbf{b'}_l$. The case when the intermediate halftone blocks are constrained to have either all black or all white pixels is shown. Such constraints are required for intermediate halftone estimation at the decoder.

Stability result 1: *If every continuous-tone image block* $\mathbf{x}(\mathbf{m})$ *satisifies the condition* $\sum_{i=0}^{3} x_i(\mathbf{m}) \in [\frac{1}{4}, \frac{3}{4}]$ *then encoder is stable.*

proof:

The proof of this result follows by induction. If $\sum_{i=0}^{3} x_i(\mathbf{m}) \in [\frac{1}{4}, \frac{3}{4}]$, then the average quantization error for the first image block $\sum_{i=0}^{3} e_i(\mathbf{m}) \in [-\frac{1}{4}, \frac{1}{4}]$ since the average of the output encoded image block lies in the set $\{\frac{1}{4}, \frac{3}{4}\}$ irrespective of the particular codeword that is used. Since the error filter coefficients sum to unity the feedback signal $f(\mathbf{m}+\delta)$ at the next scan location lies in the range $[-\frac{1}{4}, \frac{1}{4}]$. Since $\sum_{i=0}^{3} x_i(\mathbf{m}+\delta) \in [\frac{1}{4}, \frac{3}{4}]$, the modified input block at the next scan location $\mathbf{u}(\mathbf{m})$ satisfies $\sum_{i=0}^{3} u_i(\mathbf{m}) \in [0, 1]$ which results in $\sum_{i=0}^{3} e_i(\mathbf{m}+\delta) \in [-\frac{1}{4}, \frac{1}{4}]$. Thus we see that the average error due to the encoding is bounded and hence the encoder is stable.

Stability result 2: *If the fictitious codeword* $\mathbf{c}_f = [0\ 0\ 0\ 0]^T$ *is used whenever* $\sum_{i=0}^{3} x_i(\mathbf{m}) \notin [\frac{1}{4}, \frac{3}{4}]$ *then the encoder is stable for all continuous-tone inputs*

proof:

The proof of this result follows from the fact that the fictitious code word $\mathbf{c}_f$ simply reproduces the intermediate halftone block as the output encoded halftone block. It is a do-nothing code that does not embed any information. The proof is similar to the one presented above, and follows by induction.

If $\sum_{i=0}^{3} x_i(\mathbf{m}) \in [0, 1]$, then the average quantization error for the first image block $\sum_{i=0}^{3} e_i(\mathbf{m}) \in [-\frac{1}{2}, \frac{1}{2}]$ since the average of the output encoded image block lies in the set $\{0, \frac{1}{4}, \frac{3}{4}, 1\}$ irrespective of the particular codeword that is used. Since the error filter coefficients sum to unity the feedback signal $f(\mathbf{m}+\delta)$ at the next scan location lies in the range $[-\frac{1}{2}, \frac{1}{2}]$. Since $\sum_{i=0}^{3} x_i(\mathbf{m}+\delta) \in [0, 1]$, the modified input block at the next scan location $\mathbf{u}(\mathbf{m})$

satisfies $\sum_{i=0}^{3} u_i(\mathbf{m}) \in [-\frac{3}{2}, \frac{3}{2}]$ which results in $\sum_{i=0}^{3} e_i(\mathbf{m}+\delta) \in [-\frac{1}{2}, \frac{1}{2}]$. Thus we see that the average error due to the encoding is bounded and hence the encoder is stable for all continuous tone input images when fictitious codewords are allowed.

Fictitious codewords are used at the encoder to ensure encoder stability. As we shall see in the next section, fictitious codewords may also be used to trade information capacity for image quality. In any case they must be handled by the decoder.

3.3. Trading information capacity for image quality

Ignoring fictitious codewords the information capacity of an image barcode using the codeword set in Fig. 6 is 2 bits per block. Typically half of this capacity is not actually used to embed message codewords due to error correction coding. This reduces the effective capacity to 1 bit per pixel block. If fictitious codewords are used, the information capacity is image dependent and is given by

$$\text{Capacity (in bits)} = (\text{T} - \text{F}) \times \text{BPP} \times \text{ECC} \tag{8}$$

where T is the total number of image blocks, F is the total number of image blocks coded with fictitious codes, BPP is the bits encoded by the encoding alphabet per block and ECC is the loss fraction due to error control coding.

At each block location one has the choice of encoding information or not encoding information by using fictitious codewords. If a distortion metric is used to determine which blocks use fictitious codewords, then the image quality is enhanced at these locations since no information is embedded. Fig. 4(d) shows an example 216×198 image barcode with $1.2KB$ of embedded biography information. The actual rendering resolution is 150 dpi.

In the next section we discuss how the information embedded within an image barcode may be recovered from a scanned version.

4. DECODING IMAGE BARCODES

In this section we discuss how the information embedded in an image barcode may be recovered from a scan of the image barcode. As described in Section 2, first the corners are determined using the detected fiducial marks. Then a global geometric transform is applied and local shape deformations are compensated for. At this stage the the scanned barcode pixel-blocks correspond to the encoded halftone pixels as described in Section 2. The barcode is now ready for probablistic decoding. Two different scenarios for decoding exist depending on wheather the decoder has knowledge of the continuous-tone base image. Section 4.1 deals with the case when the continuous-tone base image is known at the decoder. Section 4.2 deals with the situation when the decoder has no information regarding the continuous-tone base image and must decode the information by estimating the bi-level intermediate halftone image directly from the scanned data.

4.1. Image barcode decoding when base image is known

Fig. 8 outlines the pipeline used to implement base-image guided decoding of image barcodes. To use the maximum likelihood decoding strategy of equation (3) as the probablistic decoding scheme we need to estimate the bi-level intermediate halftone image on which the encoding codewords were modulated. From Fig. 5 we see that in general the intermediate halftone B' depends not only on the continuous-tone base image but on the message codewords as well, due to the feedback mechanism in the block error diffusion. However by proper choice of codewords and block error filter we can ensure that the intermediate halftone in-fact depends only on the continuous-tone base image and not on a particular message codeword used. In fact if the block error filter has a diffusion matrix $D = 0.25\,\mathbf{1}_{4\times4}$ (which corresponds to diffusing the average block error to neighboring unprocessed pixel blocks), and the codewords all have the same average value as in Fig. 6, the diffused error block is independent of the particular codeword that is used. Thus an arbitrary message could be used to generate the intermediate halftone B' from the known continuous-tone base image B. Note that the locations of the fictitious codewords are known *a priori* from the continuous-tone base image, and they can be incorporated in the exact

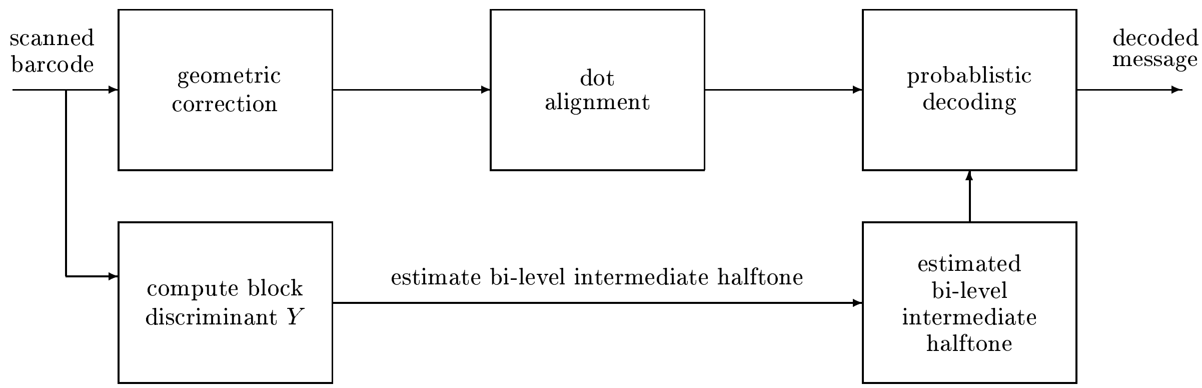

Figure 7. Decoding pipeline for image barcodes when the base image is not known. The bi-level intermediate halftone can be estimated in this case.

determination of the intermediate bi-level intermediate halftone image. Once the bi-level intermediate halftone image is determined, equation (3) is used after the laplacian probabilty model given by (1) and (2) is determined from the scanned data to decode the message codewords.

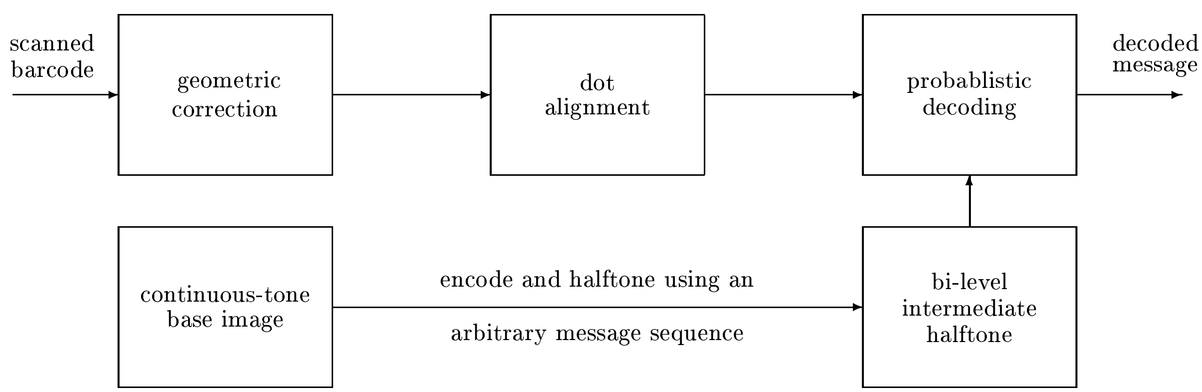

Figure 8. Decoding pipeline for image barcodes when the base image is known. The bi-level intermediate halftone can be determined exactly in this case.

4.2. Blind decoding of image barcodes

Fig. 8 outlines the pipeline used to implement blind decoding of image barcodes. The intermediate hatftone must be estimated from the scanned image barcode without knowledge of the continuous tone base-image. This imposes natural restrictions on the number of allowable intermediate patterns in the intermediate halftone image. Fig. 1 shows that the XOR encoding using two different codewords on two different base-image blocks can produce the same output encoded image block. Thus it is impossible to decide which codeword was used in encoding without knowledge of the intermediate halftone in this case. If however, the intermediate halftone were constrained to a restricted set of block patterns, then this decoding ambiguity is easily resolved. For example if we allow the intermediate halftone image blocks to be either all white or all black only as in Fig. 6 then the intermediate halftone block is clear by inspection of the corresponding encoded halftone image block. More specifically, the number of patterns allowed for an intermediate block of B' depends on a bound that permits blind decoding. For blind decoding, we must be able to infer the blocks of the intermediate halftone image B'

directly from the encoded image blocks. This means that if there are L distinct code words and the block was composed of N pixels, then we must necessarily have

$$2^N >= b'L \tag{9}$$

where there are b' distinct patterns in B' yielding $b'L$ output patterns. Thus if we are dealing with 2×2 blocks with 4 codewords, $b' <= 4$. Note that in theory, we can use more than one distinct codeword block to encode a single unique codeword to improve image quality in the encoding process. For example if we were using 2×2 blocks and encoding 2 bits/block, using 4 codeword templates with all black pixels except one, we can improve quality by adding 4 vertical/horizontal edge templates.

In practice the estimation of the bi-level intermediate halftone image must be performed from imperfect observations due to print-scan channel degradations and decoder preprocessing. After alignment there is a correspondence between a measurement patch and an encoded halftone pixel. A linear discriminant $y_i(\mathbf{m})$ is formed by multiplying the elements of the patch pointwise by a truncated Gaussian and summing. If 2×2 blocks were used in the encoding process, a new discriminant $Y(\mathbf{m})$ is formed by averaging the pixel-level discriminants $y_i(\mathbf{m})$. thus

$$Y(\mathbf{m}) = \frac{\sum_{i=0}^{3} y_i(\mathbf{m})}{4} \tag{10}$$

Fig. 9 shows the histogram of a block-level discriminant Y. From the observation $Y(\mathbf{m})$ we need to determine the intermediate the intermediate hafltone image block $\hat{\mathbf{b}'}(\mathbf{m})$. This may be done by deriving optimal thresholds to classify the codewords from the observations. This can be framed as a maximum-likelihood estimation problem. First a Gaussian mixture model is fit to the observations using the expectation maximization (E-M) paradigm. The estimation of the intermediate halftone blocks is reduced to

$$\hat{\mathbf{b}'}(\mathbf{m}) = \arg\max_{\mathbf{b}' \in \mathcal{B}} P(Y|\mathbf{b}') \tag{11}$$

where $\mathcal{B}$ represents the set of allowed intermediate halftone patterns. The individual class conditional probability distributions $P(Y|\mathbf{b}')$ are Gaussians obtained from the Gaussian mixture model. After the intermediate halftone has been estimated decoded proceeds by using equations (1) and (2) to detemine the pixel-level laplacian probablity model and then finding the codeword used to encode a given intermediate halftone image block as:

$$\hat{\mathbf{c}}(\mathbf{m}) = \arg\max_{\{\mathbf{c} \in \mathcal{C} \bigcup \mathcal{C}_f : \mathbf{w} = \hat{\mathbf{b}'}(\mathbf{m}) \otimes \mathbf{c}\}} \prod_{i=0}^{3} P(y_i|w_i) \tag{12}$$

where $\mathcal{C}$ and $\mathcal{C}_f$ denote the set of information encoding codewords and fictitious codewords respectively. Note that the fictitious codewords must be explicitly estimated in the blind decoding case while this was not required when the decoder had knowledge of the continuous-tone base image. Fig. 10(a) shows the actual intermediate halftone image. Fig. 10(b) shows the estimated intermediate halftone image from a scanned version of the image barcode.

5. CONCLUSIONS

In this paper we have shown how information may be embedded into hardcopy images using joint encoding and halftoning using block error diffusion. We have also shown how this information may be recovered from a scan of an image barcode with and without decoder knowledge of the base image.

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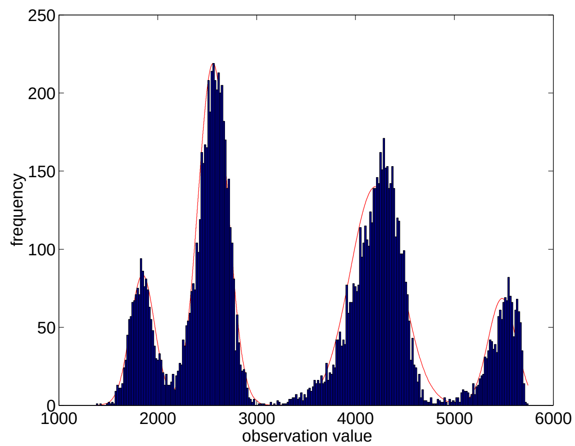
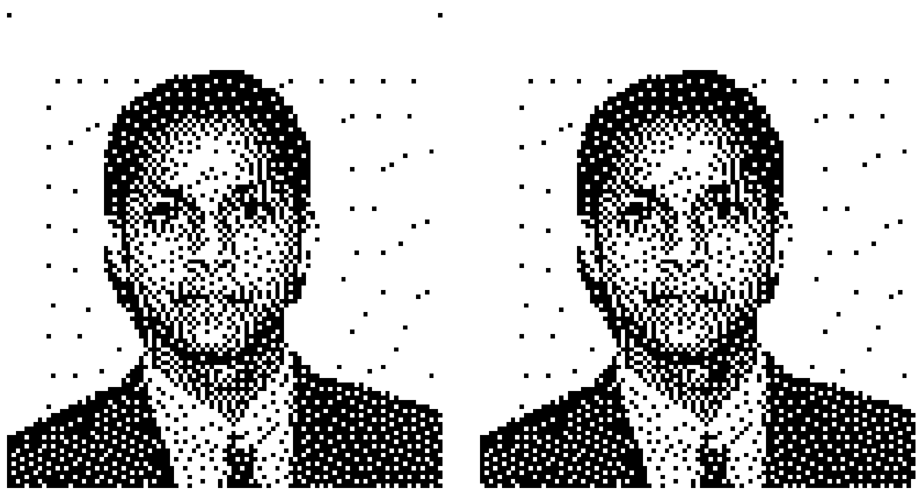


Figure 9. Histogram of observed block discriminant Y and a Gaussian mixture model fit to the observed statistics using the expectation maximization approach. The extreme modes correspond to fictitious codewords.



(a) (b)

Figure 10. Intermediate halftone estimation quality. (a) Actual intermediate halftone and (b) estimated intermediate hallftone

REFERENCES

1. D. Shaked, A. Levy, Z. Baharav, and J. Yen, "A visually significant two dimensional barcode," *Hewlett-Packard Laboratories Technical Report - HPLTR 2000-164* , 2000.
2. N. Damera-Venkata and B. L. Evans, "FM halftoning via block error diffusion," *Proc. IEEE Conf. Image Processing* , pp. 1081–1084, Oct. 2001.
3. R. Levien, "Output dependent feedback in error diffusion halftoning," *IS&T Imaging Science and Technology* **1**, pp. 115–118, May 1993.
4. R. Floyd and L. Steinberg, "An adaptive algorithm for spatial grayscale," *Proc. Soc. Image Display* **17**(2), pp. 75–77, 1976.