Hardcopy Image Barcodes Via Block-Error Diffusion

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Abstract

- Discussion
  - Block error diffusion to produce FM halftones
    - User-controlled dot size and shape
    - Using block quantization and block filtering
  - Embedding of information with block error diffusion
  - Using the print-scan-channel
  - Encoding/halftoning strategy
  - Decoding of information
  - Encoder stability

Introduction

- Background
  - Digital image halftoning
    - Quantizing a grayscale image to one bit per pixel
    - Producing a distribution of binary dots
    - Illusion of continuous tone
  - Classification of digital halftoning
    - AM , FM , AM-FM hybrid

- Proposed method
  - Method of block-error diffusion
    - Halftoning with user-defined minority dot-shapes
    - Modulation inter-dot shapes
    - Formalizing of the block-based mathematics in terms of linear algebra
  - Method of hardcopy image barcodes
    - Dot shape modulation to embed information in a 2bits/2x2bock or 1bit/pixel
    - Embedding of information in any pixel block
    - Aim : very high information capacity

Notation

- z-transform of x

$$X(z_1, z_2) = \sum_{m_1} \sum_{m_2} x(m_1, m_2) z_1^{-m_1} z_2^{-m_2} \quad (1)$$

where x : an image of vectors (a vector=NMx1, a block=NxM)

- z-transform of $\tilde{h}$

$$\tilde{H}(z_1, z_2) = \sum_{k_1=0}^{K-1} \sum_{k_2=0}^{K-1} \tilde{h}(k_1, k_2) z_1^{-k_1} z_2^{-k_2} \quad (2)$$

where $\tilde{h}$: matrix-valued filter sequence (vector=NMxNM)

- The coefficients of the matrix-valued filter ordered by rows

$$\tilde{\Gamma} = [\tilde{h}'(0) \mid \tilde{h}'(1) \mid \ldots \mid \tilde{h}'(K^2 - 1)] \quad (3)$$

where $\tilde{\Gamma}$: matrix-valued filter sequence (vector=NMxNM)

◆ Filtering operation of a multifilter $\tilde{h}$ with imput x

$$y(m_1, m_2) = \sum_{k_1=0}^{K-1} \sum_{k_2=0}^{K-1} \tilde{h}(k_1, k_2) x(m_1 - k_1, m_2 - k_2) \quad (4)$$

where y : output image of NM x 1 vectors.

◆ z-domain of y

$$Y(z_1, z_2) = \tilde{H}(z_1, z_2) X(z_1, z_2) \quad (5)$$

where : an image of vectors.

– Others

- X(m) : a scalar signal
- X(z) : z-transform
- m : 2-D index(m_1, m_2)
- k : 2-D index(k_1, k_2)

Block error diffusion

- A block diagram for block-error diffusion

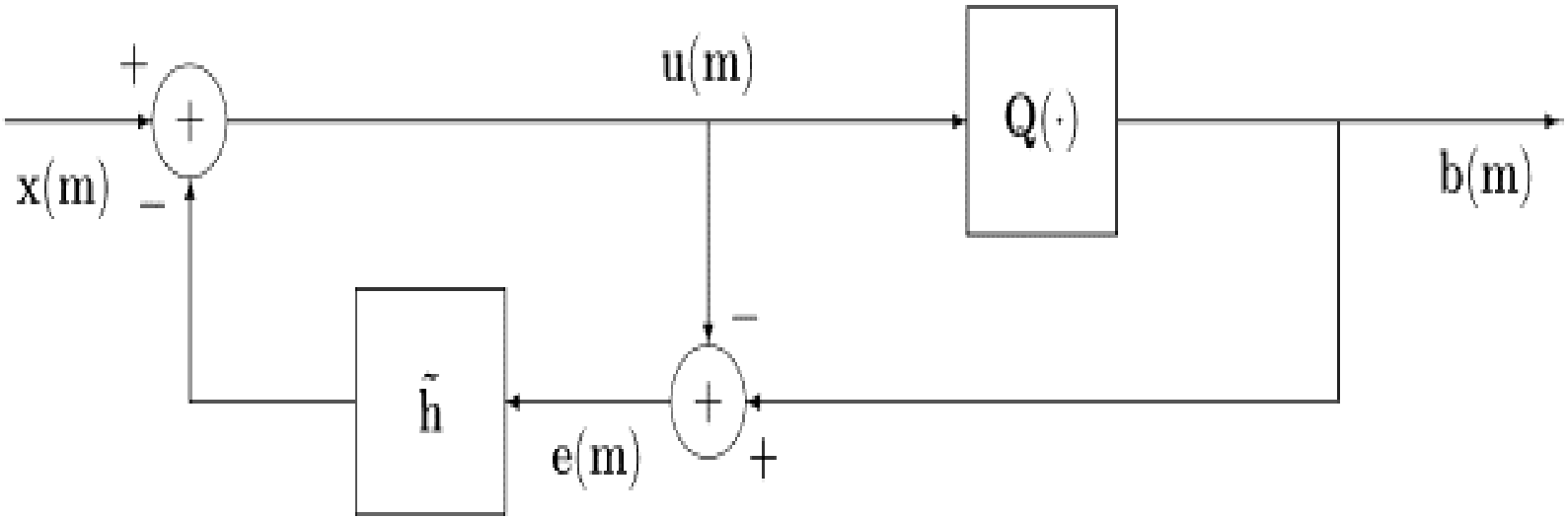


Fig.1. System block diagrams for block-error diffusion halftoning

– nput x : N x M block of pixels (called a pixel block)

– Quantizer Q(u)

$$Q(u) = \begin{pmatrix} Q(u_1) \\ Q(u_2) \\ \vdots \\ Q(u_{MN}) \end{pmatrix} \tag{6}$$

where

$$Q(u_i) = \begin{cases} 1, & u_i \geq 0 \\ -1, & u_i < 0 \end{cases} \tag{7}$$

u_i : the ith pixel value in a N x M pixel block

– Quantizer output

- One element from the discrete set o = {-1, 1}
- Black : -1, white : +1

– Feedback signal

$$f(m) = \sum_{k \in s} \tilde{h}(k) e(m-k) \tag{8}$$

where m,k : 2-D index vectors

$\tilde{h}(\cdot)$: MN x MN matrix-valued sequence

S = {(0,1),(1,0),(1,1),(1,-1)}

– Input to the quantizer

$$u(m) = x(m) - f(m) \tag{9}$$

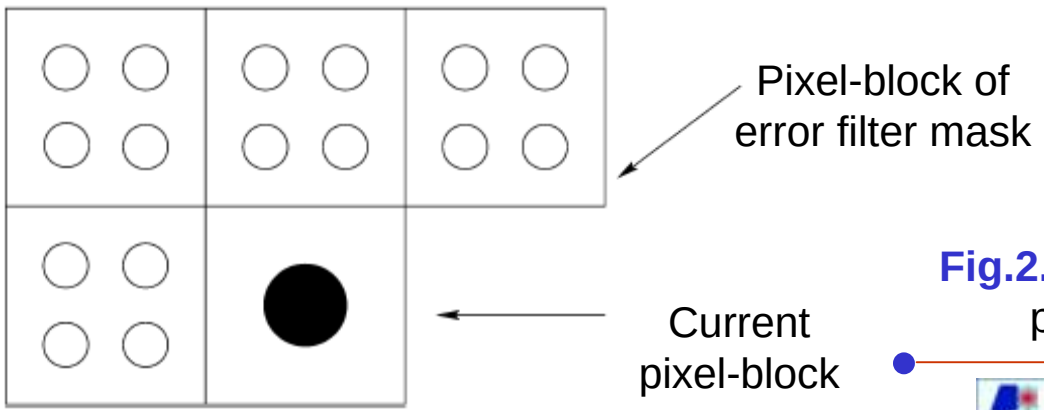


Fig.2. Block-error filter operating on pixel blocks of 2 x 2 pixels

FM Halftoning via block error diffusion

- The block-error filter
  - Governing of diffused error to the neighboring blocks
  - Conditions

$$\tilde{\Gamma} 1_{MNK^2 \times 1} = 1_{MN \times 1} \tag{10}$$

$$\tilde{\Gamma} \geq 0 \tag{11}$$

where $1_{r \times c}$: an $r \times c$ matrix of all one entries

- Error filter design
  - Coefficients by the row vector $\tilde{\Gamma}$
    - Filter size of generated error diffusion

$$\tilde{\gamma} = \left[g'(0) \mid g'(1) \mid \cdots \mid g'(K^2 - 1) \right] \tag{12}$$

– Multifilter $\tilde{\Gamma}$

$$\tilde{\Gamma} = \tilde{\gamma} \otimes \tilde{\mathrm{D}} \tag{13}$$

where $\otimes$: the Kronecker product operation

$\tilde{\mathrm{D}}$: an MN x MN diffusion matrix

the elements of $\tilde{\gamma}$: the coefficients of a conventional error filter

– Constraints of the diffusion matrix

- Governing the proportions of distributed error within the pixels of a block

$$\tilde{\mathrm{D}} 1_{MN\times 1} = 1_{MN\times 1} \tag{14}$$

$$\tilde{\mathrm{D}} \geq 0 \tag{15}$$

- FM Halftoning
  - Generated processing

Original

grayscal image

⇩ ← (to prevent aliasing)

filtering

⇩

downsampling

⇩ ← (error diffusion)

halftoning ← blurred appearance

Fig. 3. Halftone generated by pixel replication

Note the lose of high-frequency information and the blurred appearance.

– This paper's processing

- The diffusion matrix for 2 x 2 pixel clusters

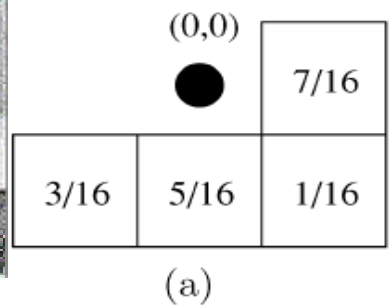
$$\tilde{D} = \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \qquad (16)$$

- Used block error filter

$$\tilde{\Gamma} = [(1/16)(5/16)(3/16)(7/16)]$$

(a) Floyd-Steninberg filter (b) Jarvis filter

Fig. 4. Block-error diffusion with block-error filters



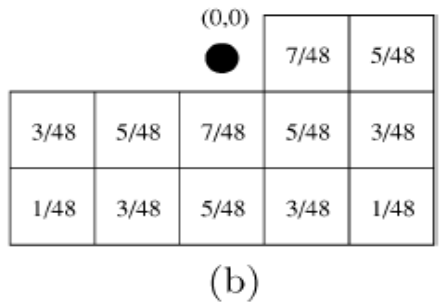


Fig. 5. Error filters

Fig.6. Block-error diffused halftones with user controlled dot shapes

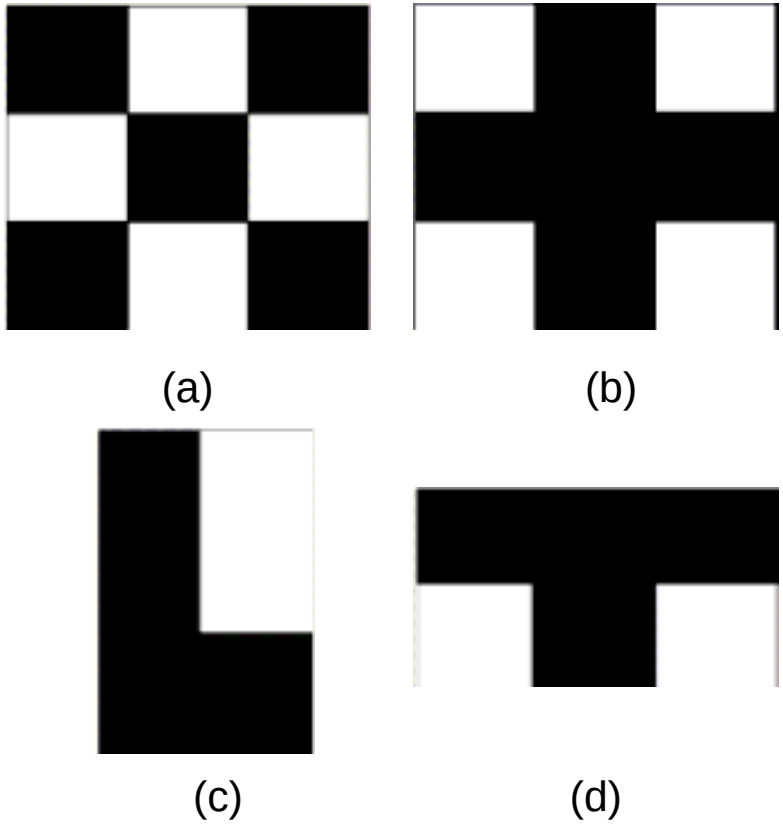


Fig.7. FM halftone dot shapes

(a)“Multiply” dots (b)“Plus” dots

(c) “L shape” dots (d)“T shape” dots

– Quantizing
  - Quantizing of majority pixel blocks by using (7)
  - Quantizing the minority pixel blocks with the desired dot shape
– Estimation of output

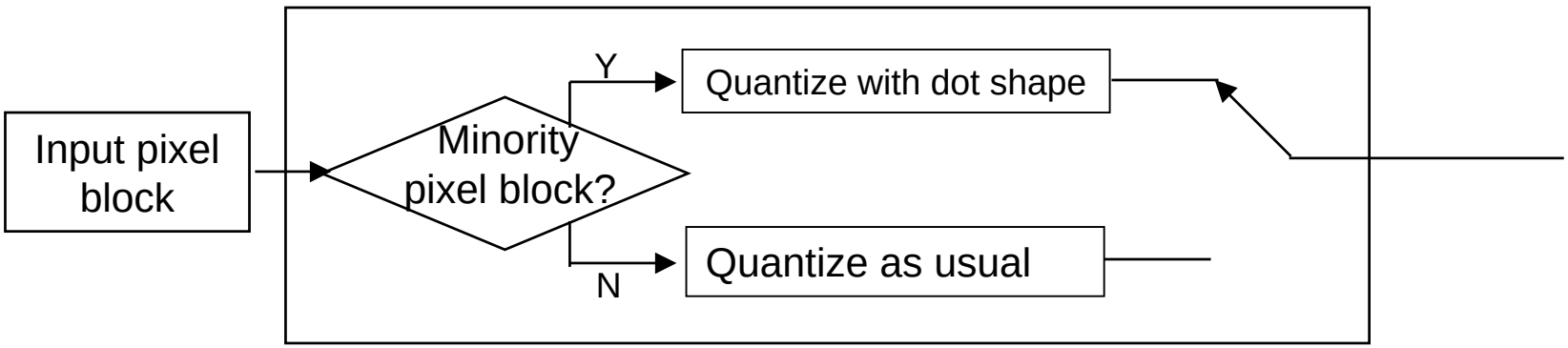


Image Barcodes

- Generating VSB
  - Halftoning
    - Producing the intermediate halftone with high-quality
  - Encoding Information
    - Producing results with low visual quality
  - Using the print-scan channel model

Fig. 8. Encoding continuous-tone images

- Proposed IBC
  - Approaching jointly encodes and halftones
  - To optimize overall encoded image quality

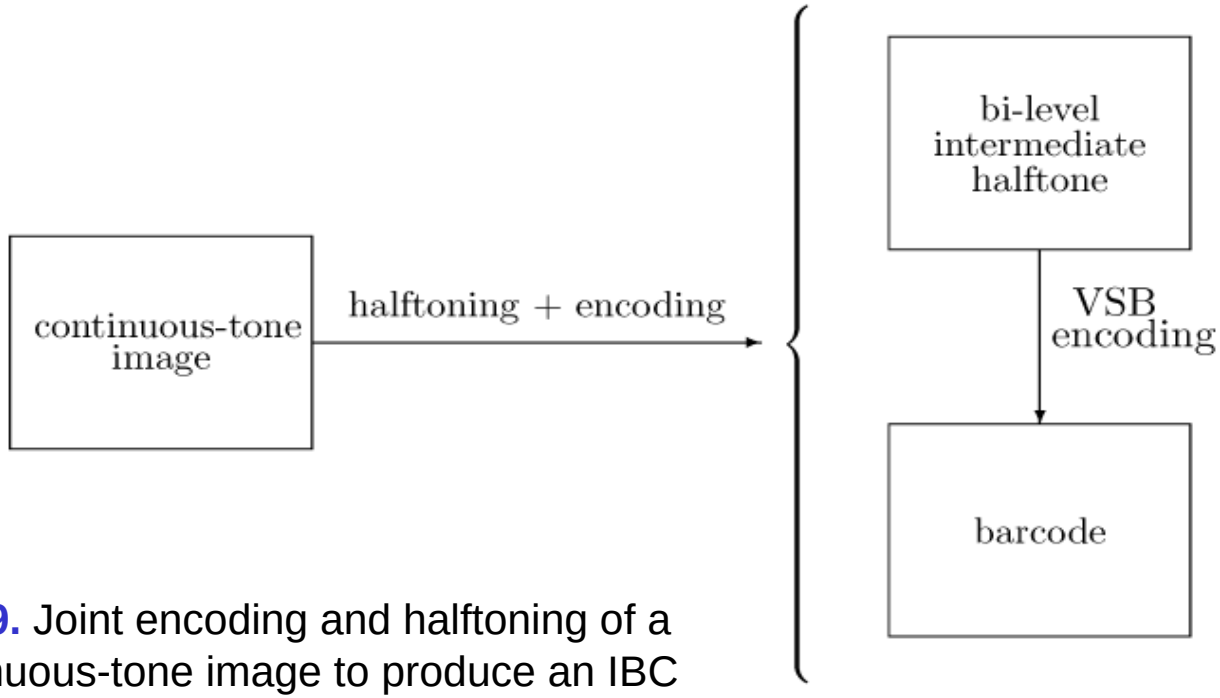
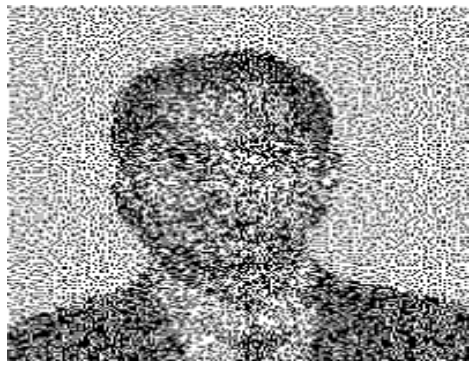


Fig. 9. Joint encoding and halftoning of a continuous-tone image to produce an IBC

(a) thresholding



(b) Floyd-steinberg

(c) Leviens's

(d) This work

Fig. 10. Barcodes generated from various intermediate halftones.

◆ Visually Significant Barcodes

– Encoding

- Insertion of fiducial marks at the corners

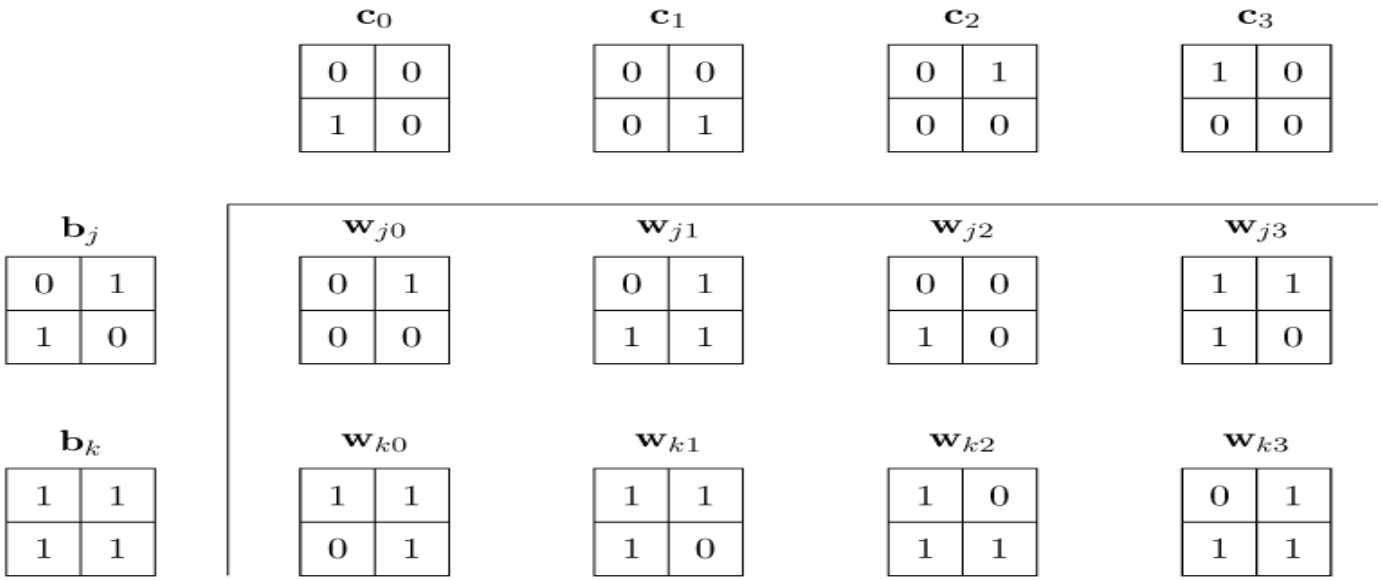
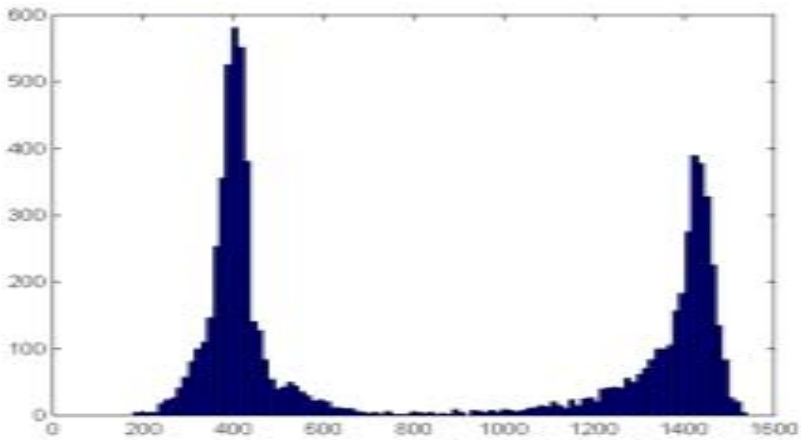


Fig. 11. Example XOR modulation encoding used in the VSB technology

w: the result of an XOR operation, c : codeword block,

b : bi-level base-image block, $w_{lm} = c_m \otimes b_l$

- Decoder
  - Operating on a scan version of the encoded hardcopy image
  - identifying of fiducial marks to enable the decoder
  - Matching between the halftone dots and the scanned image
  - A linear discriminant y
    - Form by multiplying the elements of the patch pointwise by a truncated Gaussian and summing
    - Reducing the dimensionality of the observations per encoded halftone pixel to unity



- Asymmetric Laplacian probability model

$$P(y|0) = \begin{cases} \alpha_{0L} e^{-\alpha_{0L}(\mu_0 - y)} & y < \mu_0 \\ \alpha_{0R} e^{-\alpha_{0R}(\mu_0 - y)} & y > \mu_0 \end{cases} \quad (17)$$

$$P(y|1) = \begin{cases} \alpha_{1L} e^{-\alpha_{1L}(\mu_1 - y)} & y < \mu_0 \\ \alpha_{1R} e^{-\alpha_{1R}(\mu_1 - y)} & y > \mu_{0.} \end{cases} \quad (18)$$

- Parameters

$$\{\alpha_{0L,}\ \alpha_{0R,}\ \alpha_{1L,}\ \alpha_{1R,}\ \mu_0, \mu_1\}$$

  - Estimated using an expectation maximization
  - 0 : black, 1 : white

- Decoded codeword at location m

$$\hat{c}(m) = \underset{\{c \in C: w = b(m) \otimes c\}}{\arg\max} \prod_{i=0}^{N^2-1} P(y_i \mid w_i) \quad (19)$$

where b(m) : the known bi-level base-image block at location m

$w_i \in \{0,1\}$: the encoded halftone value at location i

c : a possible codeword block

◆ Encoding Information Into an IBC

– IBC Encoder

- Processing
  - Dividing of the original image into blocks
  - The decision of intermediate halftone by thresholding the input block value
  - XOR modulation between message code word and binary block
  - Quantization error diffusion to neighboring unprocessed blocks
  - Repeating of next block until blocks have been processed

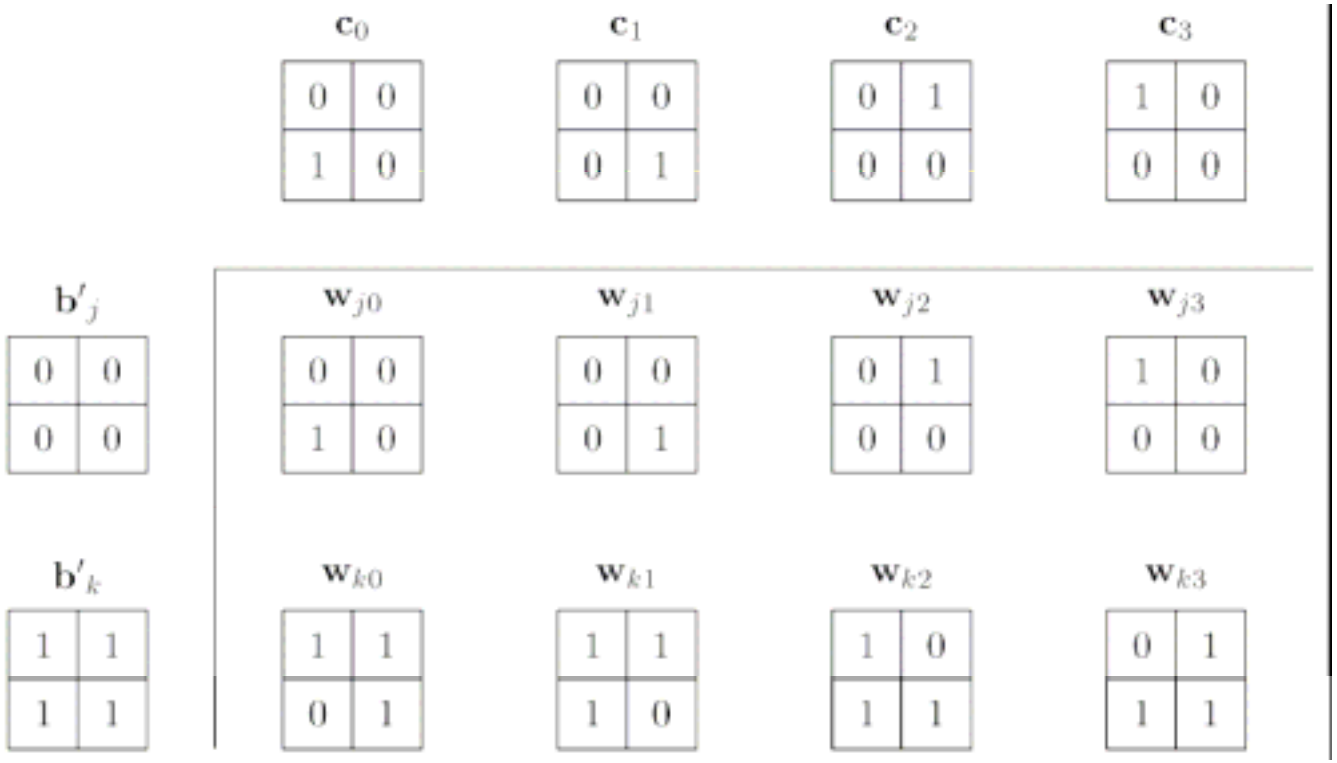


Fig. 12. Example XOR modulation encoding used in IBCs.

w: the result of an XOR operation, c : encoding codeword block ,

b : bi-level intermediate halftone block

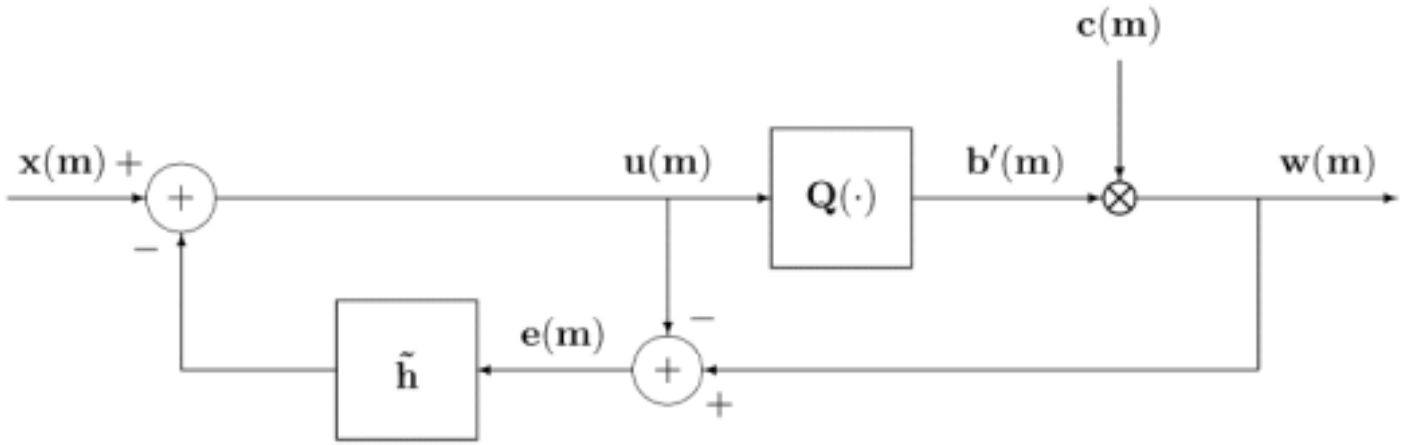


Fig. 13. system block diagram for the IBC encoder

- The intermediate halftone block

$$\mathbf{b}'(\mathrm{m}) = \mathrm{Q}(\mathrm{u}(\mathrm{m})) = \begin{cases} [1\,1\,1\,1]^T, & \sum_{i=0}^{3} u_i(\mathrm{m}) > \dfrac{1}{2} \\ [0\,0\,0\,0]^T, & \text{else} \end{cases} \tag{20}$$

- Quantization error block

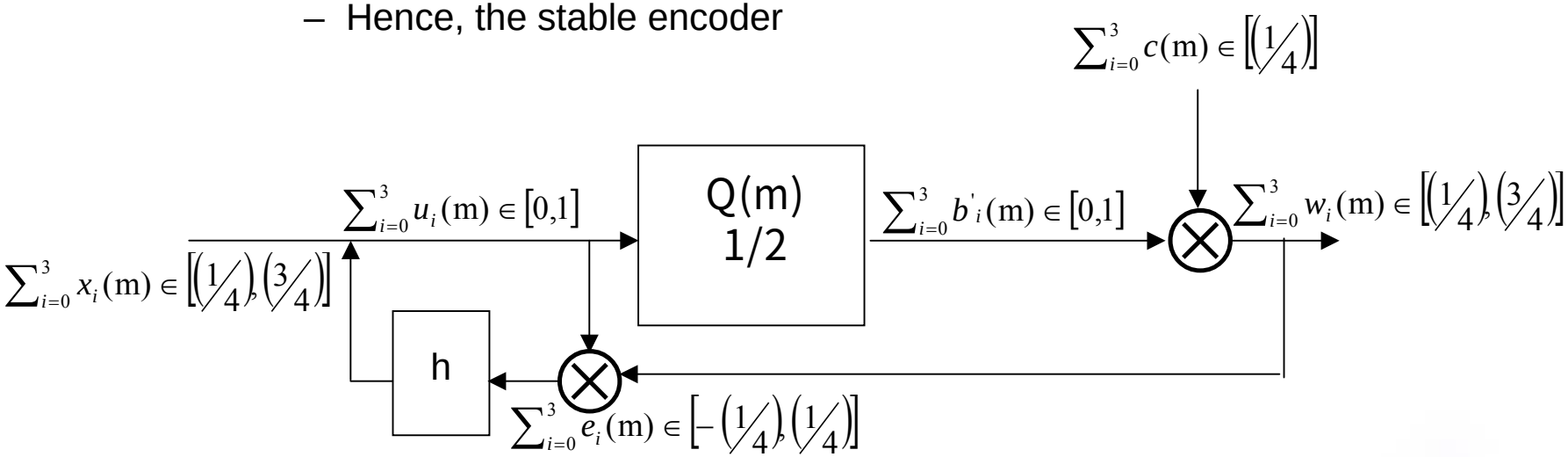
$$\mathrm{e}(\mathrm{m}) = \mathrm{c}(\mathrm{m}) \otimes \mathbf{b}'(\mathrm{m}) \tag{21}$$

- Using the block-error filter with coefficients

$$\tilde{h}(0,1) = \frac{7}{64}\mathbf{I}_{4\times4} \quad \tilde{h}(1,1) = \frac{1}{64}\mathbf{I}_{4\times4} \quad \tilde{h}(1,0) = \frac{5}{64}\mathbf{I}_{4\times4} \quad \tilde{h}(1,-1) = \frac{3}{64}\mathbf{I}_{4\times4}$$

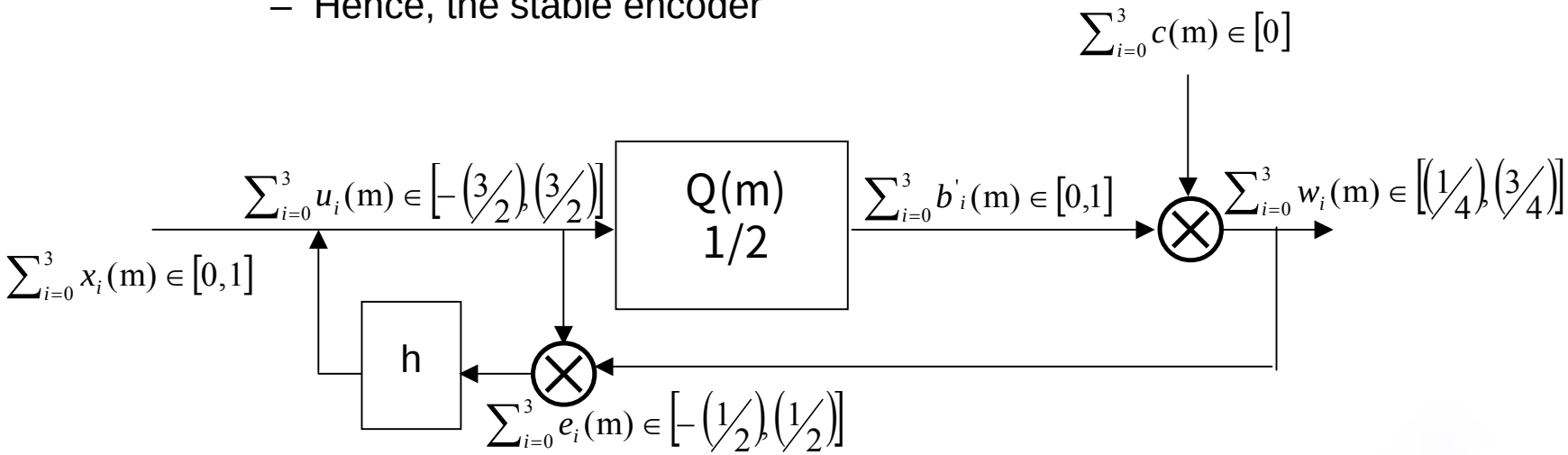
  - Floyd-steinberg weights

- Stabilizing the IBC Encoder
  - Stability Result 1
    - If x(m) satisfies the condition $\sum_{i=0}^{3} x_i(\mathrm{m}) \in \left[\left(1/4\right), \left(3/4\right)\right]$, then the encoder is stable
  - Proof
    - Bounded average error due to the encoding
    - Hence, the stable encoder



- Stability Result 2
  - If the fictitious codeword $c_f = [0\,0\,0\,0]^T$ is used whenever then the encoder is stable for all continuous-tone inputs

    $\sum_{i=0}^{3} x_i(m) \notin \left[\left(\frac{1}{4}\right), \left(\frac{3}{4}\right)\right]$
- Proof
  - Bounded average error due to the encoding
  - Hence, the stable encoder



– Trading Information Capacity for Image Quality

- Typical capacity
  - Use to embed massage codewords with only half
  - Reducing the effective capacity to 1 bit per pixel block
- The information capacity

$$\text{Capacity}(\text{in bits}) = (T - F) \times \text{BPP} \times \text{ECC} \tag{22}$$

where T : the total number of image blocks

F : the total number of image blocks coded with fictitious codes

BPP : the bits encoded by the encoding alphabet per block

ECC : the loss fraction due to error control coding

◆ Decoding IBCs

– IBC Decoding When Base Image Is Known

- Independent of the particular codeword to diffused error block
  - Having diffusion matrix $D = (1/4)\mathrm{l}_{4\times 4}$
  - Having all the same average value in the codewords

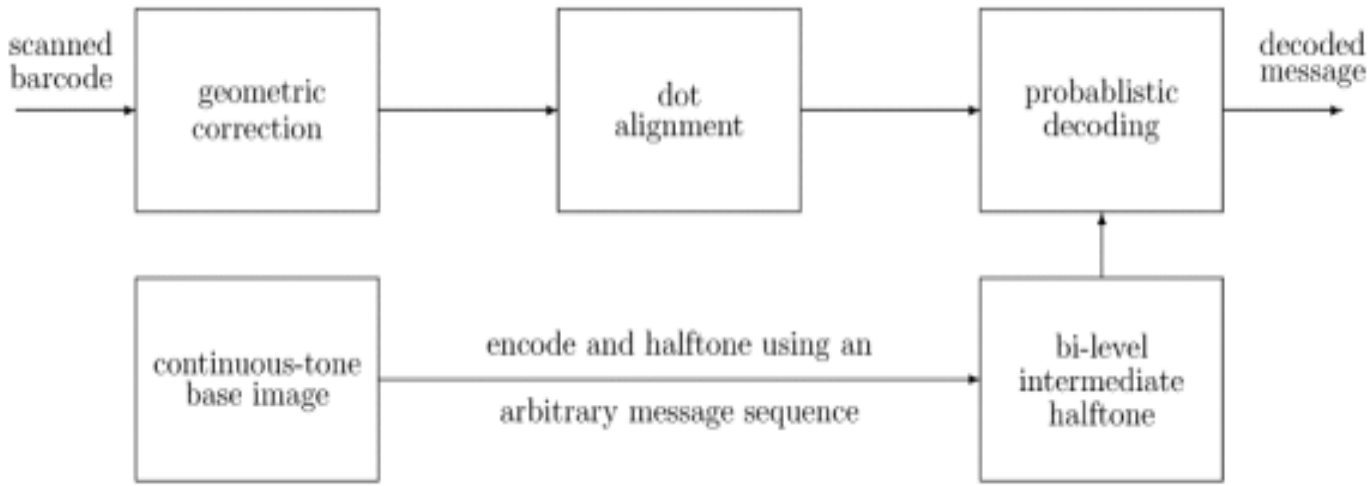


Fig.14. decoding pipeline for IBCs when the base image is known

– Blind Decoding of IBCs

- Need of estimation of intermediate halftone from the scanned IBC without knowledge
- Inferring the blocks of the intermediate halftone image B' directly from the encoded image blocks
- Conditions

$$2^N \geq b'L \tag{23}$$

where b' : distinct patterns in B' L : distinct code words

N : pixels in block

- Using more than one distinct codeword block to improve image quality in the encoding process

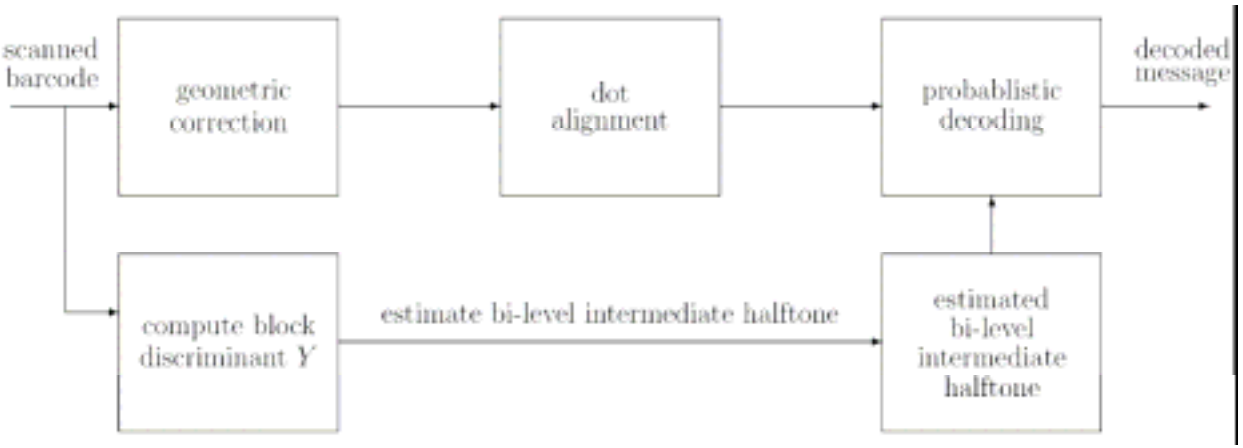


Fig. 15. Decoding pipeline for IBCs when the base image is not known

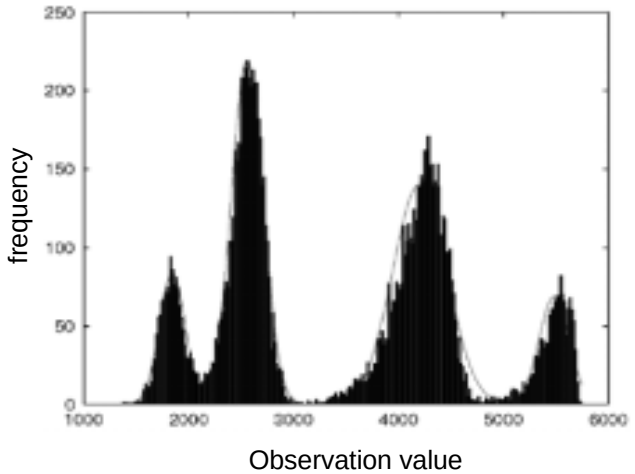


Fig. 16. Histogram of observed block discriminant Y

- Estimation of the bi-level intermediate halftone image
  - Alignment of a correspondence between a measurement patch and an encoded halftone pixel
- A linear discriminant $y_i(\mathrm{m})$
  - Form by multiplying the elements of the patch pointwise by a truncated Gaussian and summing
- E.g. $Y(\mathrm{m})$ of the encoding process with 2 x 2blocks

$$Y(\mathrm{m}) = \frac{\sum_{i=0}^{3} y_i(\mathrm{m})}{4} \qquad (24)$$

  - Need to determine the b'(m)

- Gaussian mixture model : fit to the observations using the expectation maximization paradigm

$$\hat{\mathrm{b}}'(\mathrm{m}) = \arg\max_{\mathrm{b}' \in B} P(Y \mid \mathrm{b}') \tag{25}$$

where B : set of intermediate halftone patterns

$P(Y \mid \mathrm{b}')$: Gaussians obtained from the Gaussian mixture model

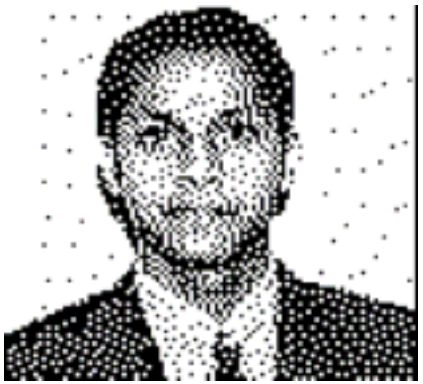
- Finding the codeword used to encode a given intermediate halftone image block

$$\hat{\mathrm{c}}(\mathrm{m}) = \arg\max_{\{\mathrm{c} \in c \cup c_f : \mathrm{w} = \mathrm{b}'(\mathrm{m}) \otimes \mathrm{c}\}} \prod_{i=0}^{3} P(y_i \mid w_i)$$

where c : set of information encoding , c_f : set of fictitious codewords

– Decoder performance

- Test : 25 test images printed on three different InkJet and LaserJet printers
- Decoding algorithm : robustness to minor image rotations
  - Result of the strong error correction codes inserted at the encoding stage.



(a)

(b)

Fig. 17. intermediate halftone estimation quality

(a) Actual intermediate halftone (b) Estimated intermediate halftone

6. Conclusion

- This paper's work
  - Introducing a framework for producing FM and AM-FM halftones with user-controlled shape and size
  - Embedment into hardcopy images using dot shape modulation within the block-error diffusion framework
  - Recovering from a scan of an IBC with and without decoder knowledge of the base image
- Next topic
  - Suitablity of block-error diffusion framework for high-addressability systems