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SECURITY CLASSIFICATION OF THIS PAGE

ADA206140

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a REPORT SECURITY CLASSIFICATION Unclassified		1b RESTRICTIVE MARKINGS	
2a SECURITY CLASSIFICATION AUTHORITY		3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.	
2b DECLASSIFICATION/DOWNGRADING SCHEDULE		4 PERFORMING ORGANIZATION REPORT NUMBER(S) NCS TIB 88-5	
5 MONITORING ORGANIZATION REPORT NUMBER(S)		6a NAME OF PERFORMING ORGANIZATION Delta Information Systems Inc.	
6b OFFICE SYMBOL (if applicable)		7a NAME OF MONITORING ORGANIZATION	
7b ADDRESS (City, State, and ZIP Code) Horsham Business Center, Bldg. 3 300 Welsh Road Horsham, PA 19044		8a NAME OF FUNDING SPONSORING ORGANIZATION National Communications System	
8b OFFICE SYMBOL (if applicable) NCS-TS		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DCA100-87-C-0078	
8c ADDRESS (City, State, and ZIP Code) Office of Technology & Standards Washington, DC 20305-2010		10 SOURCE OF FUNDING NUMBERS	
PROGRAM ELEMENT NO 33127K		PROJECT NO Q011	TASK NO 87-4
WORK UNIT ACCESSION NO			
11 TITLE (Include Security Classification) Investigation of Optional Compression Techniques for Dither Coding			
12 PERSONAL AUTHOR(S)			
13a TYPE OF REPORT Final	13b TIME COVERED FROM _____ TO _____	14 DATE OF REPORT (Year, Month, Day) April 1988	15 PAGE COUNT 80
16 SUPPLEMENTARY NOTATION			
17 COSATI CODES		18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
		Facsimile	
		Gray Scale images	
		Dither Coding	
19 ABSTRACT (Continue on reverse if necessary and identify by block number) The purpose of this study was to perform a computer simulation study in which several dither coding techniques were evaluated in order to determine their relative performances in terms of compression and output image quality in reproducing gray scale imagery transmitted over facsimile channels. Gray scale images can be represented in two ways. One method produces gray scale using multilevel pixels (i.e. each pixel can have one of 2 gray level values, where n is the number of bits of resolution of the gray scale employed). The second method simulates gray scale by locally adjusting the ratio of black pels to white pels (dithering), using spatial frequency to give the appearance of gray scale. Although the multilevel approach produces higher quality images, the dithering approach is more compatible with existing facsimile equipments.			
20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/ALIMITED ☐ SAME AS RPT ☐ DTIC USERS		21 ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a NAME OF RESPONSIBLE INDIVIDUAL Janet Orndorff		22b TELEPHONE (Include Area Code) 202-692-2124	22c OFFICE SYMBOL NCS-TS

INVESTIGATION OF
OPTIONAL COMPRESSION TECHNIQUES
FOR DITHER CODING

April 1988

Final Report

Submitted to:

NATIONAL COMMUNICATIONS SYSTEM
Office of Technology and Standards
Washington, DC 20305

Contracting Agency:

DEFENSE COMMUNICATIONS AGENCY

Contract Number - DCA100-87-C-0078

Task Order Number - 87-4

DELTA INFORMATION SYSTEMS, INC.

Horsham Business Center, Bldg. 3

300 Welsh Road

Horsham PA 19044

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REFERENCES

1.0 Introduction

This document summarizes work performed by Delta Information Systems, Inc., for the Office of Technology and Standards of the National Communications System, an organization of the U. S. Government, headed by National Communications System Assistant Manager Dennis Bodson. Mr. Bodson is responsible for the management of the Federal Telecommunications Standards Program, which develops telecommunications standards, the use of which is mandatory for all Federal agencies. The purpose of this study, performed under task order number 87-4 of contract number DCA100-87-C-0078, was to perform a computer simulation study in which several dither coding techniques were evaluated in order to determine their relative performances in terms of compression and output image quality in reproducing gray scale imagery transmitted over facsimile channels.

The CCITT is actively studying the standardization of gray scale transmission methods for facsimile. Gray scale images can be represented in two ways. One method produces gray scale using multilevel pixels (i.e. each pixel can have one of 2^n gray level values, where n is the number of bits of resolution of the gray scale employed). The second method simulates gray scale by locally adjusting the ratio of black pels to white pels (dithering), using spatial frequency to give the appearance of gray scale. Although the multilevel approach produces higher quality images, the dithering approach is more compatible with

existing facsimile equipments.

Because the dithered images consist of many short runs of black and white pels, the standard facsimile compression techniques (which are based on run-length coding) are not applicable for encoding purposes. No comprehensive study evaluating dither coding techniques as applied to facsimile transmission has been performed to date. The purpose of this task is to compare several dither coding techniques which employ alternative compression algorithms in order to determine their relative effectiveness for the addition of gray scale to the current facsimile standards.

This report is comprised of four sections. Section 1.0 provides a brief description of the objectives of the study and contains a synopsis that outlines the results obtained and conclusions made. Section 2.0 presents the technical approach employed in the study and includes a discussion of dither coding techniques, detailed descriptions of the dither coding algorithms simulated, and a discussion of the test image selection process. The results of the simulation study are presented in Section 3.0, and the conclusions and recommendations made based on these results are contained in Section 4.0.

1.1 Synopsis

Dither coding of gray scale images can be implemented in two ways, pre-transmission dithering and post-transmission dithering. Pre-transmission dithering algorithms threshold the multi-level gray scale image to 1 bit/pixel at the transmitter and then either encode the dithered image directly or rearrange the dithered image prior to encoding to improve compression. The pre-transmission dithering algorithms offer the advantage of compatibility with existing facsimile equipments. Those pre-transmission dithering algorithms in which the dithered image is encoded directly allow facsimile units with gray scale capability to transmit dithered images to non-gray scale capable units; those algorithms in which the dithered image is rearranged prior to encoding require only minor modifications to existing equipments.

Post-transmission dithering algorithms employ multi-level gray scale compression algorithms to encode the gray scale image prior to transmission. The encoded gray scale image is decoded at the receiver and then dithered so that the existing two-tone facsimile equipments can be used to display the image. Post-transmission dithering algorithms offer the advantages of multi-level gray scale imagery at the receiver and potentially high compression; the principal disadvantage associated with them is limited compatibility with existing facsimile equipments.

In this study, seven pre-transmission dithering algorithms

and four post-transmission dithering algorithms were evaluated. Of the seven pre-transmission dithering algorithms, four employed clumped dithering and three employed ordered dithering. The four post-transmission dithering algorithms employed clumped dithering. Clumped dithering is an electronic approximation of the photo-mechanical screening process; an irregularly shaped matrix of fixed thresholds, arranged so that a "dot" grows outward from the center as successively darker gray levels are encountered, is employed to reduce the multi-level gray scale image to 1 bit/pixel. Ordered dithering employs an 8 x 8 matrix of fixed thresholds, arranged symmetrically so that four "dots" grow in the corners of the square matrix, to reduce the multi-level gray scale image to 1 bit/pixel.

The four pre-transmission dithering algorithms in which clumped dithering was employed include straight clumped dithering, adaptive clumped dithering, clumped dithering with clump plane separation, and adaptive clumped dithering with clump plane separation. In straight clumped dithering, the gray scale image is thresholded using the clumped dither threshold matrix; the dithered image is then Group 4 encoded directly, without further processing. In adaptive clumped dithering, the gray scale image is processed in 8 x 8 blocks of pixels; the pixels in each block are thresholded with either the clumped dither thresholds or a single user-specified threshold, depending upon the contents of the block.

In clumped dithering with clump plane separation, the gray

scale image is thresholded as in straight clumped dithering, then separated into clump planes, where each clump plane is comprised of the pixels thresholded with one of the thresholds in the clumped dither matrix. The clump planes are then Group 4 encoded. In adaptive clumped dithering with clump plane separation, the gray scale image is thresholded as in straight adaptive dithering. However, the blocks thresholded with the clumped dither matrix thresholds are placed in one image (Image X), the blocks thresholded with the user-specified threshold are placed in a second image (Image Y), the pixels in Image X are rearranged into clump planes, and both images are Group 4 encoded.

The three pre-transmission dithering algorithms in which ordered dithering was employed include straight ordered dithering, adaptive ordered dithering with bit reordering, and adaptive ordered dithering with bit interleaving. In straight ordered dithering, the gray scale image is thresholded using the ordered dither threshold matrix; the dithered image is then Group 4 encoded directly, without further processing.

In adaptive ordered dithering with bit reordering, the gray scale image is processed in 8 x 8 blocks of pixels; the pixels in each block are thresholded with either the ordered dither thresholds or a single user-specified threshold, depending upon the contents of the block. The pixels in those blocks in which the ordered dither thresholds were employed are rearranged to improve the compressibility of the dithered image. The

rearranged blocks are identified at the receiver by examining the block identification image; for each 8 x 8 block in the dithered image, there is a corresponding identification bit in the block identification image which determines whether the block has been reordered. Both the dithered image and the block identification image are Group 4 encoded prior to transmission.

In adaptive ordered dithering with bit interleaving, the gray scale image is thresholded as in adaptive ordered dithering with bit reordering. However, the blocks thresholded with the ordered dither matrix thresholds are placed in one image (Image X), the blocks thresholded with the user-specified threshold are placed in a second image (Image Y), the pixels in Image X are rearranged to produce more contiguous black and white run lengths, and both images are Group 4 encoded.

The four post-transmission dithering algorithms evaluated in this study employed adaptive clumped dithering to threshold the reconstructed multilevel gray scale images at the receiver. Two of the post-transmission dithering algorithms involved variations of a conditional DPCM coding algorithm previously studied by Delta Information Systems. The first variation employed a three-neighbor gray level value predictor, a non-linear three-bit quantizer, and Huffman entropy coding to encode multi-level gray scale images prior to transmission. The second variation employed a staggered horizontal 2:1 subsampler and corresponding interpolator in addition to the predictor, quantizer, and entropy coder mentioned above.

Two of the post-transmission dithering algorithms employed transform coding techniques to encode the multi-level gray scale images prior to transmission. Both transform coding algorithms employ the discrete cosine transform (DCT) to transform the input images prior to quantization. In the adaptive zonal coding algorithm, quantization involves discarding all but a selected number of transform coefficients that are located in a specific zone of each image sub-block. In the image dependent Chen-Smith coding algorithm, quantization involves a relatively complex series of statistical, classification, and bit allocation steps designed to produce high compression in low detail regions of the gray scale image and better image quality in high detail regions.

The results of the simulations performed in this study indicate that the pre-transmission dithering algorithms produce a better combination of compression and image quality than the post-transmission dithering algorithms. The adaptive clumped dithering with clump plane separation algorithm performed best in terms of both compression and image quality. The adaptive ordered dithering with bit interleaving algorithm produced the highest compression of the algorithms simulated, followed closely by the adaptive ordered dithering with bit reordering algorithm; the image quality produced by the adaptive ordered dithering algorithms was not as good as that produced by the adaptive clumped dithering algorithms. The adaptive clumped dithering algorithm produced the best image quality and would require the fewest hardware modifications to implement.

The post-transmission dithering algorithms produced image quality that was inferior to that produced by the pre-transmission dithering algorithms; this is due to the additional distortion added to the gray scale images by the quantization step prior to dithering. The post-transmission dithering algorithms employing transform coding could have produced significantly more compression, but would have done so at the expense of image quality. Post-transmission dithering techniques offer the advantage of a reconstructed multi-level gray scale image at the receiver, but would require significant hardware modifications to implement.

2.0 TECHNICAL APPROACH

2.1 Compression Techniques

Figure 2.1 illustrates the wide range of gray scale coding techniques which could be employed in implementing a gray scale option for facsimile. The principal advantage offered by dither coding is its compatibility with existing facsimile equipment; dither coded images can be displayed using typical bilevel (black/white) output devices. There are several dithering techniques currently available, including random dithering, clumped dithering, and ordered dithering.

Of these three, random dithering is the least complex to implement, and it produces relatively good quality in terms of pseudo-gray scale rendition¹; however, the random nature of this technique eliminates any redundancy characteristics inherent in the input image and thus limits the compressibility of the dithered image. The clumped and ordered dithering techniques both employ threshold matrices which, to some extent, preserve the redundancy inherent in the input image; thus, the dithered images these techniques produce are more compressible. In this study, both clumped and ordered dithering techniques were

¹ Pseudo-gray scale rendition is a method of conveying gray scale information on a binary output device by varying the ratio of black pixels to white pixels over a given area.

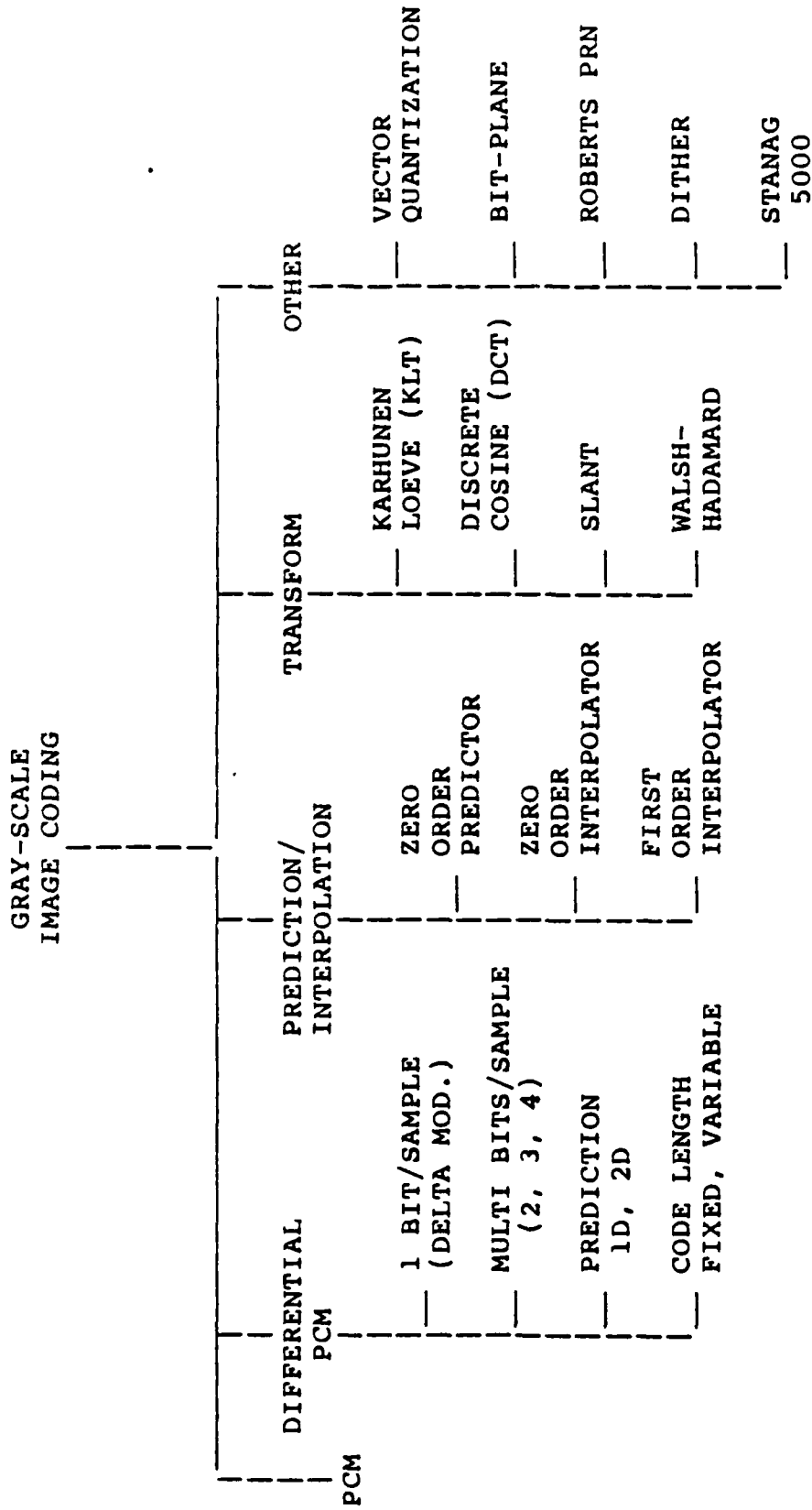


FIGURE 2.1 GRAY SCALE CODING TECHNIQUES

evaluated in order to determine which is the most effective in terms of compression and output image quality.

There are two basic ways in which dither coding algorithms can be implemented. On one hand, the gray scale images can be dithered prior to transmission, in which case the receiving unit can be any existing facsimile machine. This method would allow facsimile machines with gray scale capabilities to transmit gray scale documents to units without such capabilities, and thus would require a minimum of hardware modifications. Gray scale images can also be compressed and transmitted using multilevel gray scale compression techniques such as DPCM or transform coding and then dithered at the receiver. Post-transmission dithering offers the advantages of multilevel gray scale image availability at the receiver and potentially higher compression; however, it would limit the transmission of gray scale images to connections between gray scale-capable facsimile units. In this study, several algorithms of each type were simulated in order to evaluate their relative performances.

2.1.1 Pre-Transmission Dithering Techniques

Pre-transmission dithering techniques generally consist of two processing steps. The first step involves the thresholding of the multilevel gray scale image to produce a binary (1 bit/pixel) dithered image. In this study, two dithering schemes were evaluated, clumped dithering and ordered dithering.

The second step involves compressing the dithered image, either directly or after rearranging the image to improve compression. Seven dithered image compression schemes were evaluated in this study, three in which the dithered image is compressed directly and four in which the dithered image is first rearranged.

Those techniques in which the dithered image is compressed directly offer the advantage of minimal modification to existing facsimile equipment; only the transmitting unit requires upgrading. Three such techniques were simulated in this study, straight clumped dithering, adaptive clumped dithering, and straight ordered dithering. The compression techniques in which the dithered image is rearranged prior to compression are somewhat less compatible in that the receiving unit must be able to reconstruct the dithered image from the rearranged data it receives. Four compression techniques of this type were simulated in this study, clumped dithering with clump plane separation, adaptive clumped dithering with clump plane separation, ordered dithering with adaptive bit reordering, and ordered dithering with adaptive bit interleaving. All seven compression techniques employ the Modified READ II algorithm (as outlined in CCITT Recommendation T.6) to compress the dithered images.

The clumped dither coding technique is an electronic approximation of the photo-mechanical screening process. It employs a matrix of fixed thresholds which are arranged in such a way that a "dot" grows outward from the center as successively

darker gray levels are encountered in low contrast regions of the image. The ordered dither coding technique also employs a matrix of fixed thresholds in which the threshold values are arranged so that four dots grow symmetrically in the four corners of the 8 x 8 square matrix.

2.1.2 Post-Transmission Dithering Techniques

Post-transmission dithering techniques employ multilevel gray scale compression algorithms to encode gray scale documents at the point of transmission and to decode them at the point of reception. The received gray scale images are then dithered so that they may be printed by standard facsimile equipment. Post-transmission dithering methods offer the advantage of reconstructed multilevel gray scale images at the receiver, but do so at the expense of equipment modification requirements.

As Figure 2.1 indicates, there are many multilevel gray scale compression techniques currently available. Two of these techniques, differential pulse code modulation (DPCM) and transform coding, were employed in this study. Simulations of several DPCM and transform coding algorithms were performed by Delta Information Systems in previous studies (Refs. 1,2). The results of those simulations were used in this study to select the best DPCM and transform coding algorithms in terms of compression and output image quality.

2.2 Algorithm Descriptions

Figure 2.2 is a block diagram of the simulation software employed in this study. Several of the software modules depicted in Figure 2.2 were developed by Delta Information Systems in previous studies (i.e. DPCM, transform coding, Group 4 encoding/decoding, clumped dithering) and are thus described briefly in this report. The algorithms associated with the software modules developed specifically for this study (i.e. adaptive clumped dithering, clump plane separation, ordered dithering with bit interleaving, ordered dithering with bit reordering) are described in detail below.

2.2.1 Clumped Dithering

Dither coding is a process in which multilevel gray scale images are quantized, or thresholded, to 1 bit/pixel in such a way that the gray scale of the multilevel image can be displayed on a bilevel output device. Clumped dithering is an electronic approximation of the photo-mechanical screening process. It employs an irregularly shaped matrix of fixed thresholds, as shown in Figure 2.3. The thresholds are arranged so that a "dot" grows outward from the center as successively darker gray levels are encountered in low contrast regions of the image (an emulation of the photo-mechanical dot screen). Figure 2.4 is an illustration of how the irregularly shaped clump matrices

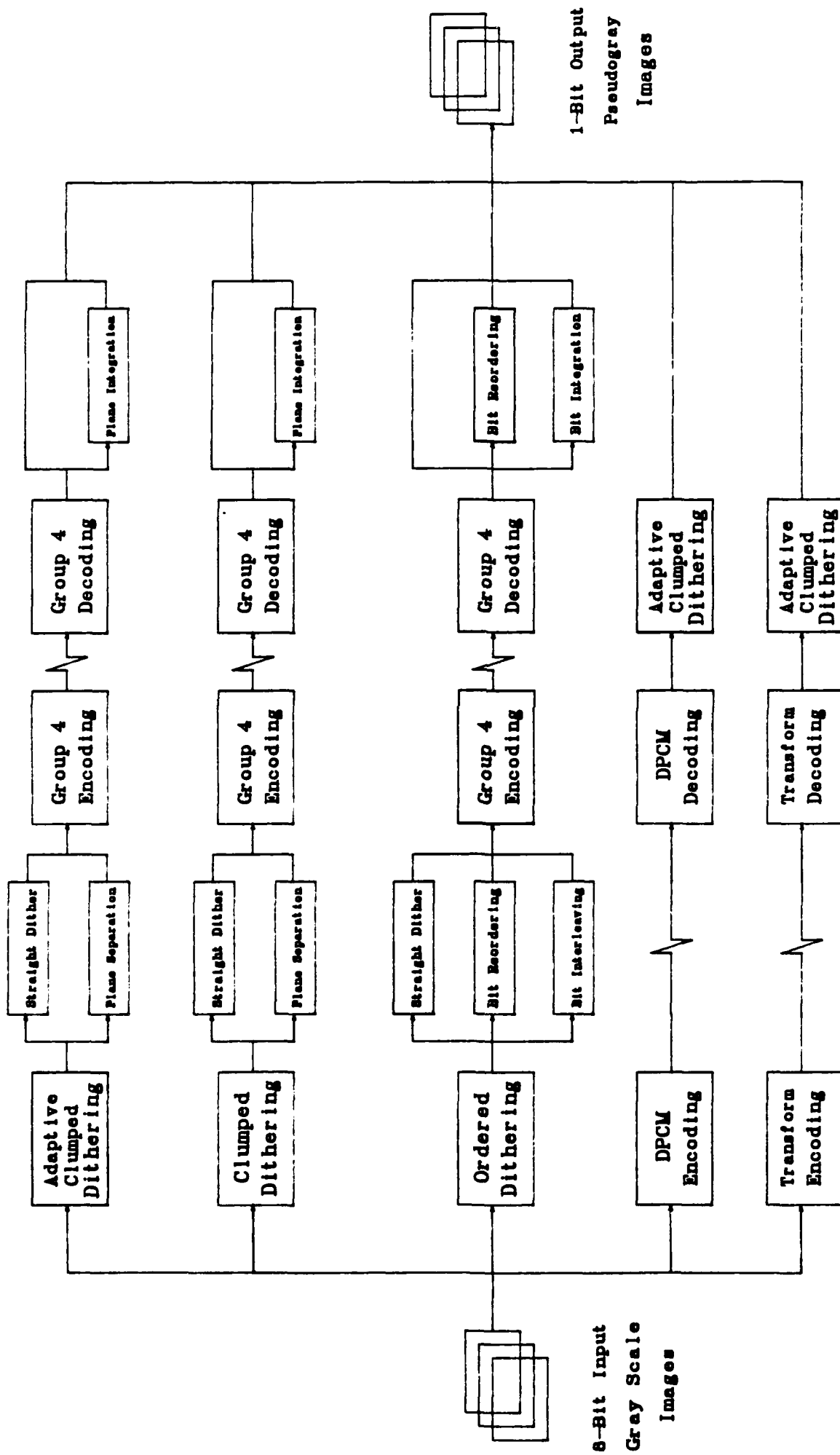


Figure 2.2 - Simulation Software Block Diagram

		167	200	
230	210	94	72	
153	111	36	52	193
	216	181	126	222
	242	232		

Figure 2.3 - Clumped Dither Threshold Matrix

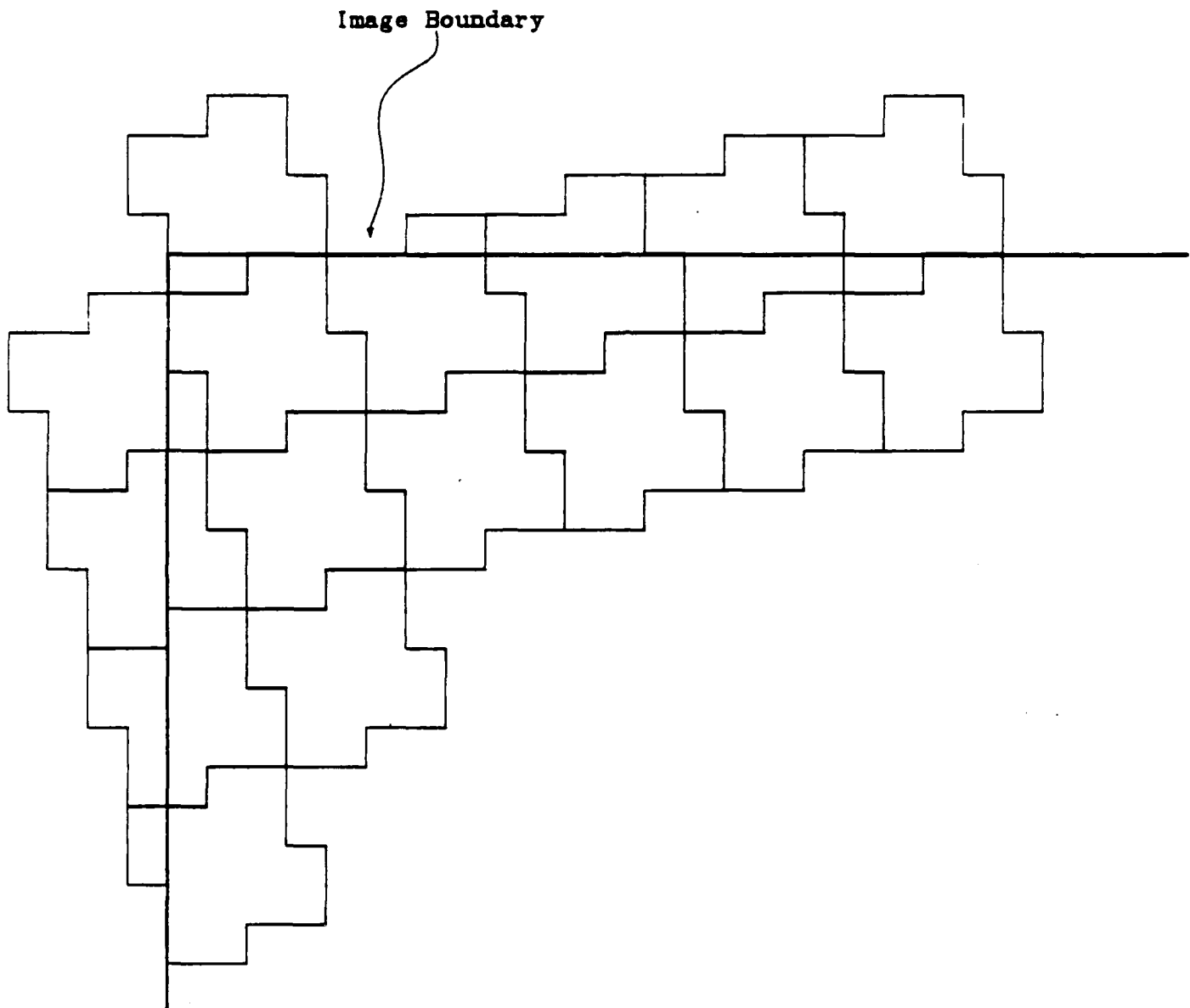


Figure 2.4 - Clumped Dither Matrix Lattice

interconnect to form a lattice in order to process the rectangular images.

The 8-bit gray level of each input pixel is compared to one of the matrix thresholds; which threshold is used depends upon the position of the pixel within the image. The color of the 1-bit output pixel is dependent upon whether the gray level value of the input pixel is greater than (black) or less than (white) the dither threshold. The set of thresholds and their arrangement determine gray scale range, frequency, and other half tone image properties. Clumped dithering produces images with accurately reproduced high contrast detail while generating a full pseudo-gray scale (Ref. 3).

Clumped dithered images can be compressed directly using existing facsimile coding techniques (Group 4 encoding), but generally do not compress as well as typical two-tone documents. This is due to the fact that the concept of dither coding, in which the spacing between individual (or groups of) black pixels is varied to produce pseudo-gray scale rendition, does not lend itself well to run length coding schemes that rely on long, contiguous runs of black and/or white pixels to achieve compression. The adaptive clumped dithering technique to be described shortly produces a slight improvement in compression and significantly improves image quality for images containing both gray scale and two-tone information. The clump plane separation algorithm, also to be discussed shortly, is designed to provide a significant improvement in compression without any

significant improvement in compression without any loss in image quality.

2.2.1.1 Adaptive

Straight clumped dithering of gray scale images produces excellent image quality in most cases. However, when the image contains a significant amount of two-tone information (e.g. identification photos), the image quality of the two-tone areas is highly distorted. The multilevel pixels that fall on black-white boundaries produce a "graying" effect in the dithered image. Letters, symbols, and sharp edges appear blurred; the resolution of the two-tone areas is limited.

The adaptive clumped dithering algorithm significantly improves the quality of the two-tone areas by applying a separate thresholding technique to these areas to eliminate the "graying" effect. Unlike the straight clumped dithering algorithm, in which the image is processed one pixel at a time, the adaptive clumped dithering algorithm processes the image in 8 x 8 pixel blocks. The maximum and minimum gray level values of each block are first determined; the difference between these two values is then used to determine the "distinction" of the block. The block distinction is termed high if the difference exceeds a user-selectable threshold, and is considered low otherwise.

A low distinction block contains, in general, appreciable gray scale content, and is thus thresholded with the appropriate clumped dither thresholds (see Figure 2.5). If the block

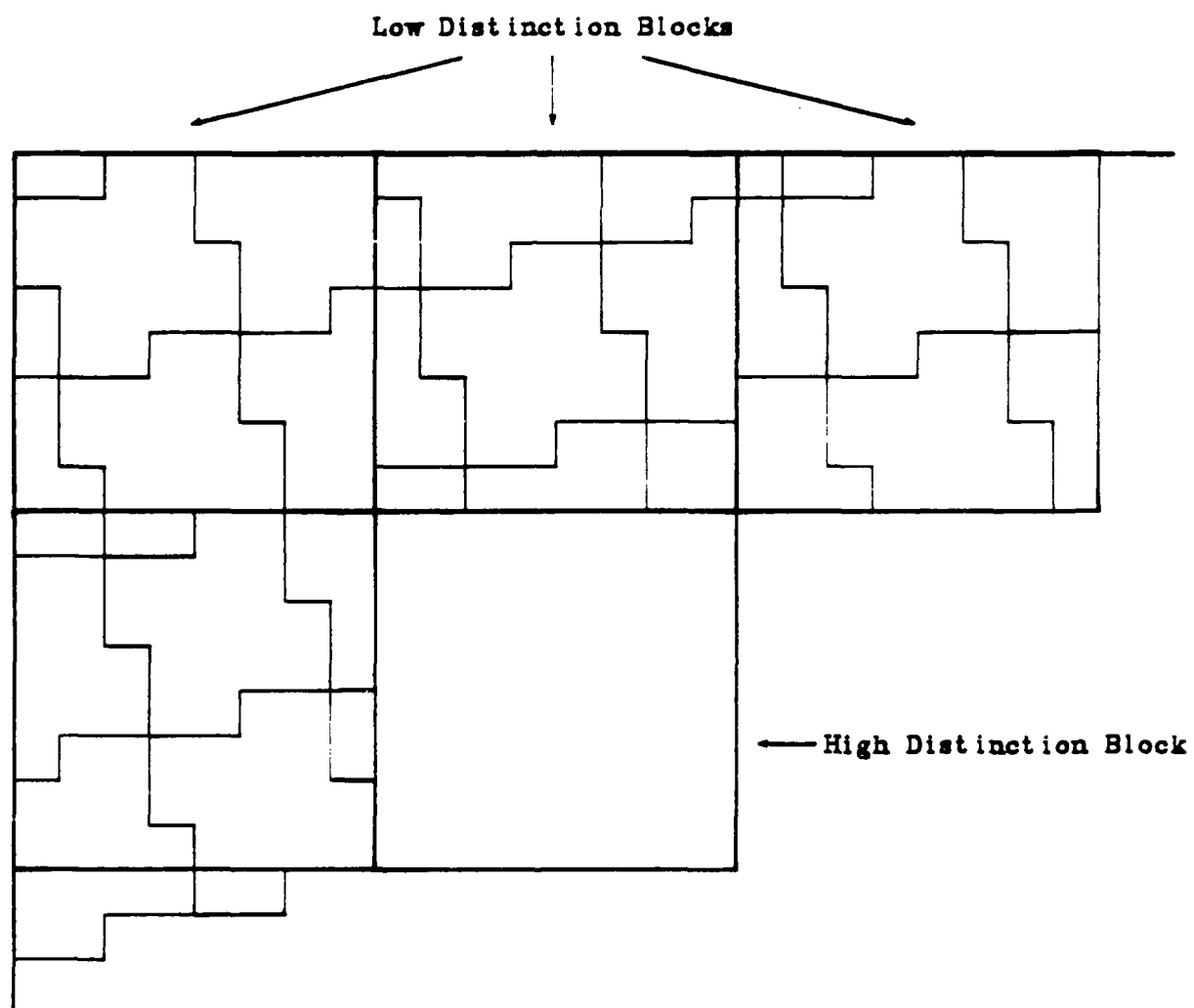


Figure 2.5 - Adaptive Clumped Dithering Process

distinction is determined to be high, the block contains predominantly two-tone or sharp-transition information. These blocks are thresholded by using a single user-selectable threshold; this eliminates the blurring of sharp edges by making the pixels on black-white boundaries with higher gray level values always black and pixels with lower values always white. When the clumped dither thresholds are employed on two-tone image areas, some of the boundary pixels with higher gray level values are thresholded with very high clumped dither thresholds (e.g. 232) and thus are set white; likewise, some of the boundary pixels with lower gray level values are thresholded with very low clumped dither threshold values (e.g. 36) and thus are set black. These improperly thresholded boundary pixels are what causes the "graying" of the sharp edges.

In addition to improving the quality of dithered images containing an appreciable amount of two-tone information, adaptive clumped dithering marginally improves the compressibility of the image by removing the short runs produced by the "graying" effect. The adaptive nature of this algorithm has little effect, either positive or negative, on images containing little or no two-tone information.

2.2.1.2 Clump Plane Separation

Dither coding reduces the information content of a gray scale image to 1 bit/pixel. Direct compression of a dithered

image using typical facsimile run-length coding techniques can produce additional compression, but can also yield negative compression (i.e. a run-length encoded image containing more data than the un-encoded image). By rearranging the data in the dithered image prior to run-length encoding, compression performance can be enhanced. Clump plane separation is an example of an image rearrangement technique.

In clump plane separation, a dithered image is separated into 17 planes, where each plane is comprised of the pixels thresholded by one of the thresholds in the clumped dither matrix. As Figure 2.6 illustrates, the pixel in matrix position 1 of every clumped dither matrix is placed in plane 1, the pixel in matrix position 2 of every clumped dither matrix is placed in plane 2, and so on. Placing all of the pixels compared to the same threshold together, in most cases, increases the length of black and/or white runs, thus making the image more compressible.

The 17 clump planes are then compressed using Group 4 encoding. At the receiver, the planes are all decoded, and the dithered image is reconstructed from the clump planes by placing each pixel back in the position from which it was extracted at the transmitter. Clump plane separation provides enhanced compression, in most cases, with no effect on image quality. Clump plane separation does not perform well (in terms of compression) on clumped dithered images containing a significant amount of two-tone information.

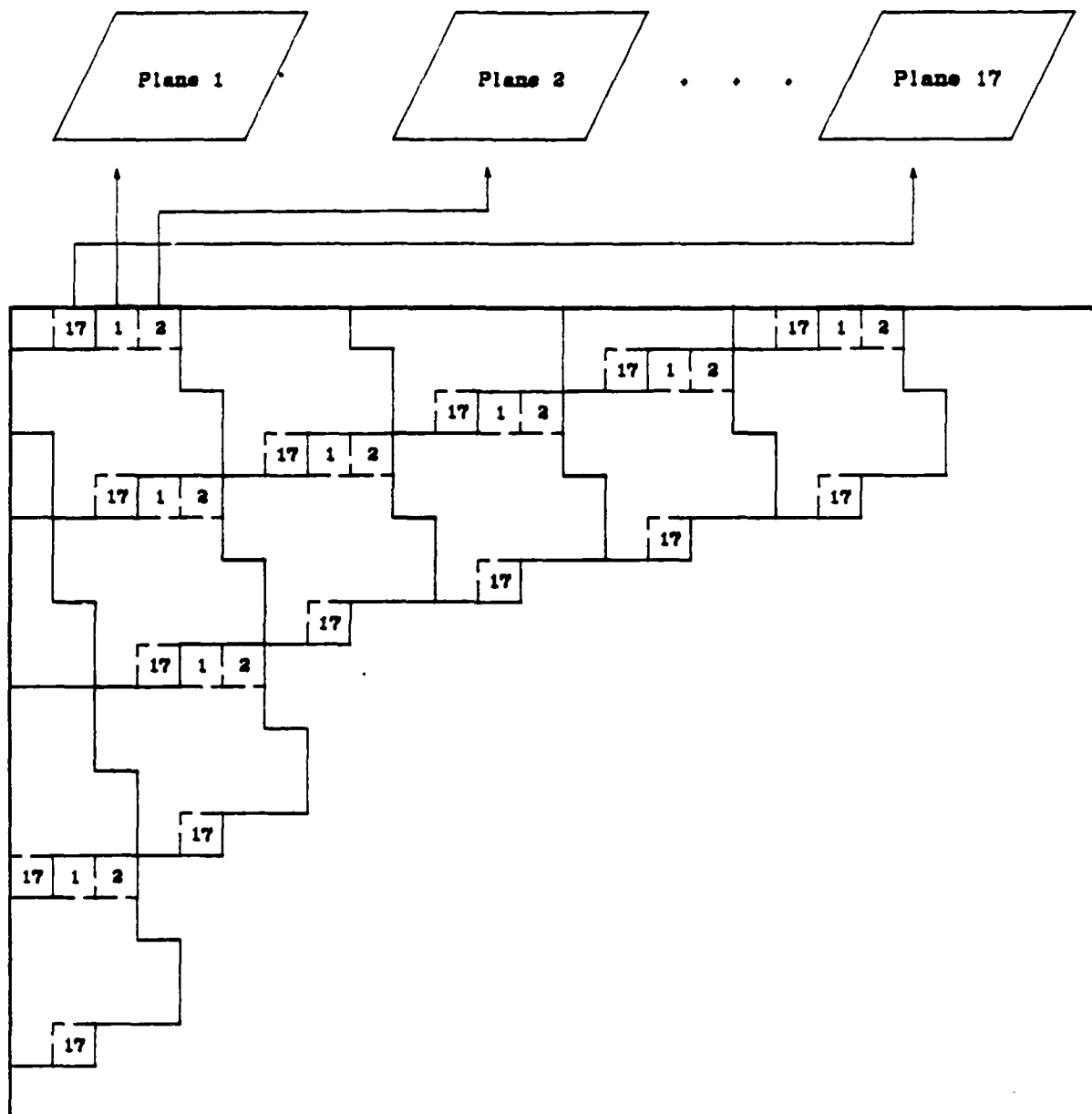


Figure 2.6 - Dither Plane Separation Process

2.2.1.3 Adaptive with Clump Plane Separation

By combining adaptive clumped dithering with clump plane separation, an optimum combination of compression and output image quality is achieved for clumped dithered images. Adaptive clumped dithering with clump plane separation is somewhat different than the two algorithms from which it was developed in that the output is two separate images rather than one. As with adaptive clumped dithering, the image is processed in 8 x 8 pixel blocks, and the distinction of each block is determined. If the block distinction is determined to be high, the user-specified threshold is used for every pixel in the block, and the block is placed in Image Y; at the same time, an all-white 8 x 8 pixel block is placed in Image X. If the block distinction is found to be low, the clumped dither thresholds are used, the dithered block is placed in Image X, and an all-white block is placed in Image Y.

Clump plane separation is then applied to Image X, and the two images are encoded separately using Group 4 encoding. At the receiver, the two images are decoded, the clump planes of Image X are re-integrated, and the low distinction blocks from Image X and the high distinction blocks from Image Y are combined to reconstruct the original adaptively clump dithered image. This algorithm is the least image dependent of the clumped dithering techniques studied; two-tone information has little effect on the compression or image quality achieved.

2.2.2 Ordered Dithering

Ordered dithering employs an $n \times n$ matrix of fixed thresholds that is repeated throughout the image, just as in clumped dithering. The distribution of the thresholds within the matrix is designed so that it provides acceptable pseudo-gray scale rendition and edge sharpness while producing a minimum of visible patterns and/or artifacts. The ordered dither matrix employed in this study is an 8×8 matrix in which the thresholds are arranged symmetrically, as shown in Figure 2.7.

The even-numbered thresholds (2-30) are arranged spirally in the upper-right and lower-left hand corners, and the odd-numbered thresholds (1-31) are arranged spirally in the upper-left and lower-right hand corners. This arrangement provides 32 pseudo-gray scale levels with a pattern of four "dots" growing in each of the four corners of the matrix as successively darker gray levels are encountered in low contrast regions of the image.

Ordered dithering processes gray scale images in 8×8 pixel blocks. The 8-bit gray level of each input pixel is quantized to 5 bits and compared to one of the matrix thresholds; which threshold is used depends upon the position of the pixel within the block. The color of the 1-bit output pixel is dependent upon whether the quantized gray level value of the input pixel is greater than (black) or less than (white) the dither threshold. The 8-bit to 5-bit quantization step is equivalent to using 32

25	19	11	27	24	18	10	26
9	1	3	21	8	1	2	20
17	7	5	13	16	6	4	12
31	15	23	29	30	14	22	28
24	18	10	26	25	19	11	27
8	1	2	20	9	1	3	21
16	6	4	12	17	7	5	13
30	14	22	28	31	15	23	29

Figure 2.7 - Ordered Dither Threshold Matrix

quantization levels spread linearly over an 8-bit dynamic range (0-255).

Ordered dithered images can be compressed directly using existing facsimile coding techniques (Group 4 encoding), but generally do not compress as well as typical two-tone documents. This is due to the fact that the concept of dither coding, in which the spacing between individual (or groups of) black pixels is varied to produce pseudo-gray scale rendition, does not lend itself well to run length coding schemes that rely on long, contiguous runs of black and/or white pixels to achieve compression. The adaptive bit reordering technique to be described shortly produces a significant improvement in compression while also improving image quality for images containing both gray scale and two-tone information. The adaptive bit interleaving algorithm, also to be discussed shortly, is also designed to provide a significant improvement in compression while improving the image quality of images containing both gray scale and two-tone information.

2.2.2.1 Adaptive Bit Reordering

Straight ordered dithering of gray scale images produces very good pseudo-gray scale rendition, but at the expense of compression. The dithered images produced are not very compressible, and, if the image contains two-tone information, the two-tone areas are highly distorted. The multilevel pixels

that fall on black-white boundaries produce a "graying" effect in the dithered image. Letters, symbols, and sharp edges appear blurred; the resolution of the two-tone areas is limited.

Adaptive ordered dithering works in the same way that adaptive clumped dithering (described earlier) works. The image is processed in 8 x 8 blocks of pixels. The maximum and minimum gray level values of each block are first determined; the difference between these two values is then used to determine the "distinction" of the block. The block distinction is termed high if the difference exceeds a user-selectable threshold, and is considered low otherwise.

A low distinction block contains, in general, appreciable gray scale content, and is thus thresholded with the appropriate ordered dither thresholds (see Figure 2.8). If the block distinction is determined to be high, the block contains predominantly two-tone or sharp-transition information. These blocks are thresholded by using a single user-selectable threshold; this eliminates the blurring of sharp edges by making the pixels on black-white boundaries with higher gray level values always black and pixels with lower values always white.

The bit reordering algorithm is designed to produce large contiguous black and white areas by rearranging the pixels in each 8 x 8 block. As Figure 2.9 illustrates, after the pixels are thresholded, they are rearranged so that the resulting black pixels are packed more closely together in the block (as are the

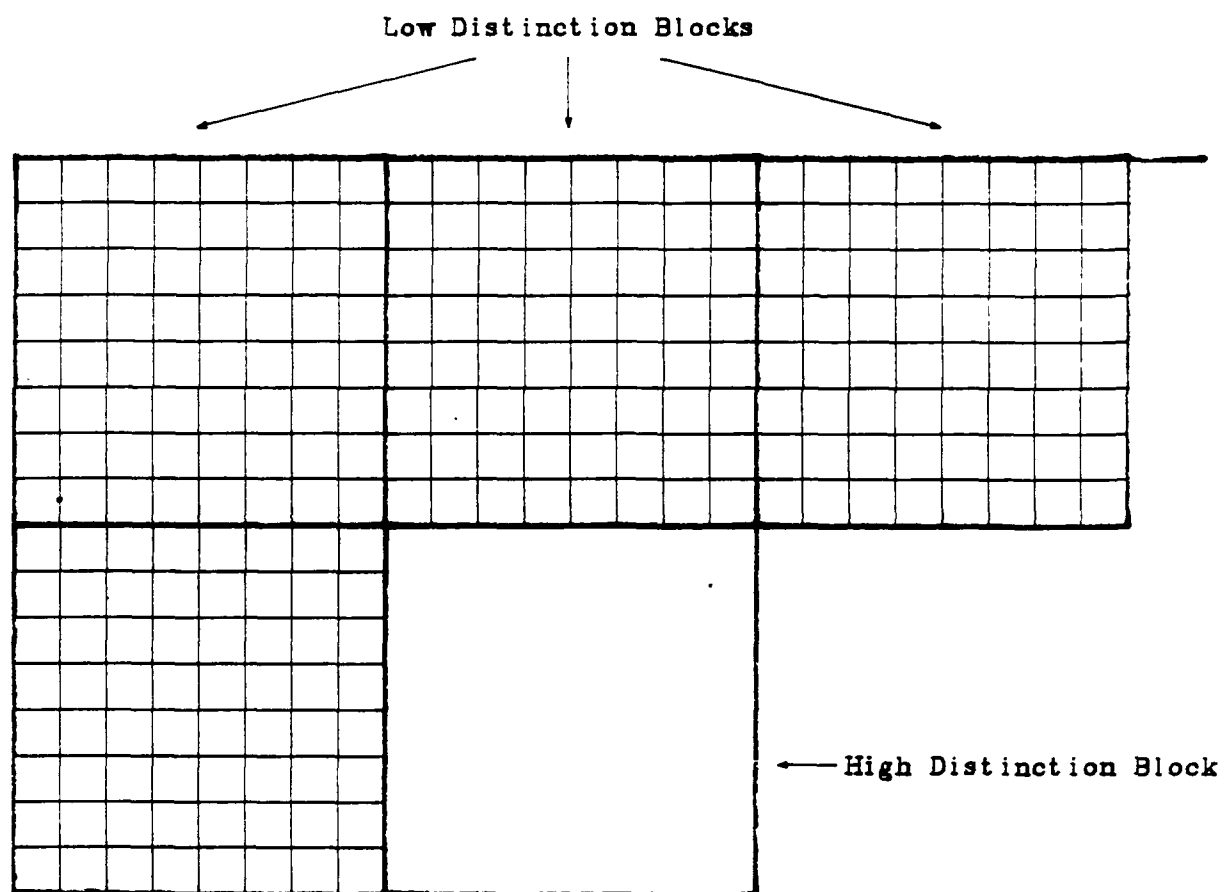


Figure 2.8 - Adaptive Ordered Dithering Process.

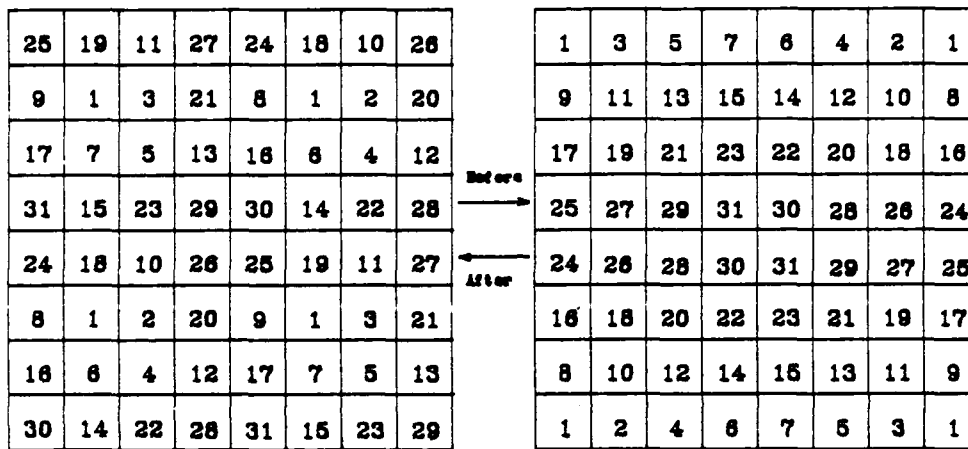


Figure 2.9 - Bit Reordering Block Rearrangement Process

white pixels). The threshold values are used in Figure 2.9 to illustrate the dithered pixel rearrangement pattern.

In adaptive bit reordering, only the low difference blocks are reordered; reordering the high difference blocks would not yield more compressible data. Although one reordered dithered image is produced, a second image, called a block identification image, is required in order to identify the reordered blocks at the receiver. This image consists of 1 bit for each 8 x 8 block in the dithered image. This bit is set to 1 if the block has been reordered and to 0 if it has not. Both the reordered dithered image and the block identification image are then Group 4 encoded for transmission.

At the receiver, both images are first decoded; the block identification bit for each 8 x 8 block is then used to determine whether or not the block has been reordered. If it has, the reverse of the reordering process (see Figure 2.9) is employed to restore the original dithered block. Adaptive bit reordering produces excellent image quality, even in images containing two-tone information, and relatively high compression, particularly in images containing large, smooth areas of slowly changing gray scale (Ref. 4).

2.2.2.2 Adaptive Bit Interleaving

The adaptive bit interleaving algorithm is similar to the adaptive bit reordering algorithm in that it is designed to

produce large contiguous black and white areas, but it does so by rearranging the pixels in the entire image rather than in each 8 x 8 block. The gray scale and two-tone areas are separated into low distinction and high distinction blocks in the same way. However, two images are produced, as in the adaptive clumped dithering with clump plane separation algorithm. Low distinction blocks are placed in Image X (with a corresponding all-white block placed in Image Y) and high distinction blocks are placed in Image Y (with a corresponding all-white block placed in Image X).

Image Y is Group 4 encoded directly, but Image X is first rearranged to make it more compressible. Figure 2.10 illustrates the bit interleaving process. The pixels thresholded with similar thresholds are extracted from each block in the image grouped together so that the black pixels are packed more closely together in the image (as are the white pixels). The threshold values are used in Figure 2.10 to illustrate the dithered pixel rearrangement pattern. Image X is then Group 4 encoded as well, and both images are transmitted.

At the receiver, both images are first decoded. Image X is then re-integrated to recover the low distinction blocks, and the low distinction blocks from Image X and the high distinction blocks from Image Y are combined to reconstruct the original adaptively clump dithered image. Adaptive bit interleaving produces excellent image quality and very high compression, relatively independent of image content (Ref. 4).

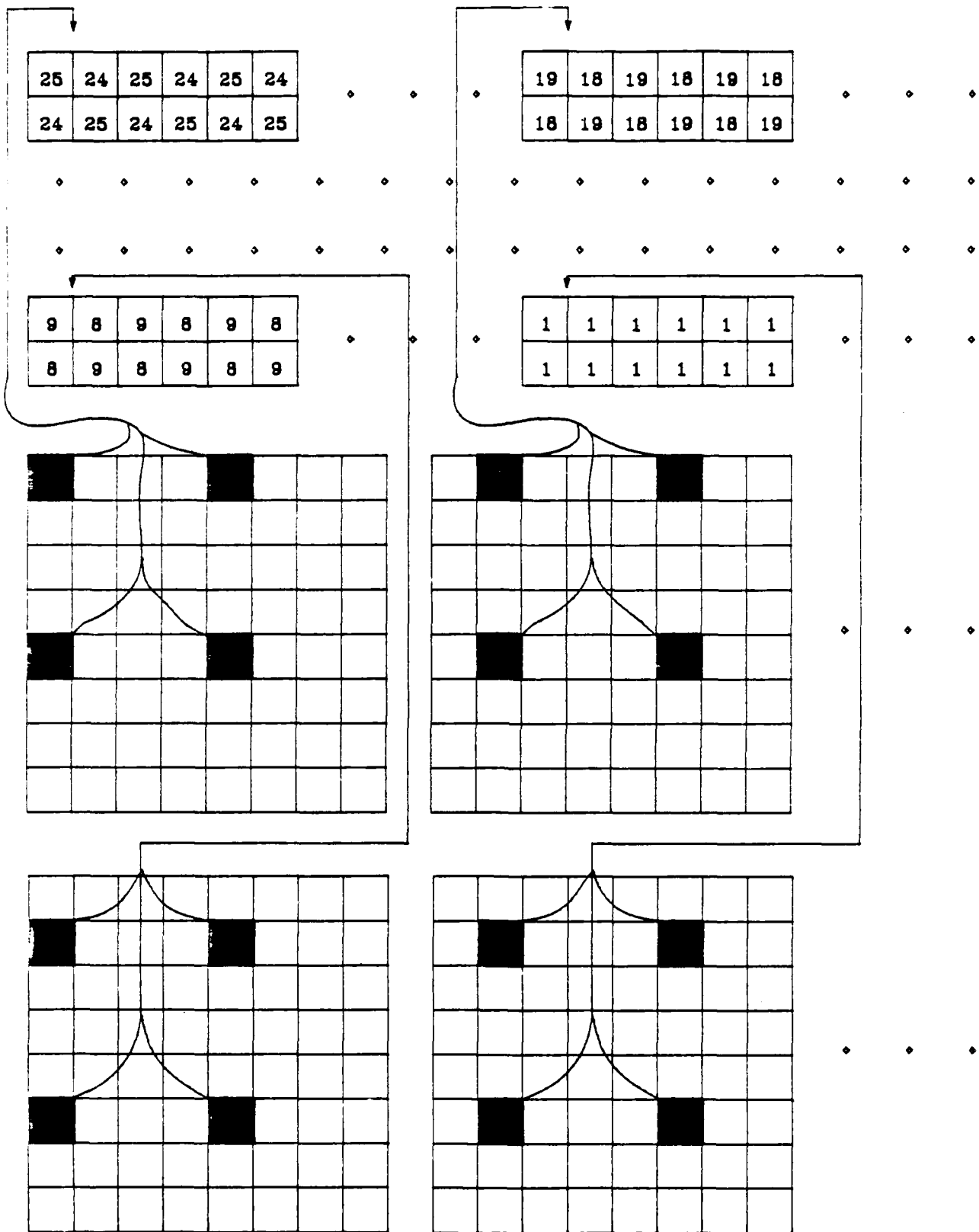


Figure 2.10 - Bit Interleaving Image Rearrangement Process

2.2.3 DPCM Coding

Differential pulse code modulation (DPCM) compression techniques encode a gray scale image by predicting the gray level value of each pixel based on the gray level values of previously transmitted pixels and quantizing (to a fixed number of bits) the difference between the predicted value and the actual value. The pixels are reconstructed at the receiver by running the same gray level predictor as that used in the transmitter and then adding the corresponding quantized difference value. Entropy coding is sometimes used to further compress the quantized data. Differences between DPCM algorithms generally consist of differences in predictor, quantizer, and/or entropy coder design.

The DPCM compression algorithm employed in this study was selected based on the results of a study previously performed by Delta Information Systems (Ref. 1). Conditional DPCM employs a three-neighbor gray level value predictor, a non-linear three-bit quantizer, Huffman entropy coding, and an optional staggered horizontal subsampler and corresponding interpolator. The gray level value of each pixel is predicted based on the reconstructed values of three previously transmitted pixels. The difference between the actual and predicted gray level values is quantized into one of seven representative quantizer levels, and the pixel is represented in the quantized data stream by a 3-bit level number (e.g. 111 for level 7).

The quantized data (3 bits/pixel) is then further compressed using Huffman entropy coding. The Huffman codes employed were generated from the local conditional statistics of each test image, based on the number of occurrences of each four pixel group in the image (three neighboring pixels and the current pixel). The compression performance of this DPCM algorithm has a theoretical lower bound of 1 bit/pixel. The optional staggered 2:1 horizontal subsampler reduces this lower bound to 0.5 bits/pixel by removing half of the pixels in the image. The subsampling is staggered from line to line in order to provide for a more efficient interpolation scheme at the receiver.

2.2.4 Transform Coding

Transform coding algorithms, generally speaking, operate as two step processes. The first step involves performing linear transformations on the original signal (separated into sub-blocks of $n \times n$ pixels each), in which signal space is mapped into transform space. In the second step, the transformed signal is compressed by encoding each sub-block through quantization. At the receiver, the reconstruction operation involves performing an inverse transformation of each decoded transformed sub-block. The function of the transformation operation is to make the transformed samples more independent than the original samples, so that the subsequent operation of quantization may be done more efficiently.

The two transform coding algorithms employed in this study were selected based on the results of a previous study performed by Delta Information Systems (Ref. 2). Both algorithms employ the discrete cosine transform (DCT) to transform the input images. The DCT was selected because of its excellent performance and comparatively simple implementation. The two transform coding algorithms differ in how the transform coefficients are quantized prior to transmission.

The adaptive zonal transform coding technique is a hybrid scheme providing the benefits of both zonal and threshold coding. In straight threshold coding, a specific energy amplitude is selected, and only those transform coefficients in a sub-block that are above this threshold value are retained; the other coefficients are discarded. A major disadvantage to threshold coding is the overhead required to store information regarding the location within the sub-block of the coefficients which are retained. Zonal coding quantizes only those coefficients in a specified area, or zone; because the positions of the retained coefficients are known, the information concerning their locations need not be stored.

In the adaptive zonal coding algorithm, coefficients in a specified zone are compared to a selected threshold value in an ordered pattern until a coefficient value below the threshold is encountered. When a coefficient below the selected threshold is encountered, the remaining coefficients in the specified zone are discarded, as are all of the coefficients outside of the zone.

The only overhead required by the adaptive zonal coding technique is to store the number of coefficients retained in each sub-block. After the significant coefficients have been extracted from the sub-block, they are normalized and quantized to a fixed number of bits through various arithmetic operations based on general image statistics. At the receiver, arithmetic operations to reverse the normalization process are performed to produce reconstructed transform coefficients (with quantization error) in the specified zone of the sub-block; all of the coefficients discarded in the encoding process are set to zero, and the reconstructed sub-block is ready to be inversely transformed.

The second transform coding algorithm employed in this study is an image-dependent variation of the Chen-Smith technique. The basic Chen-Smith coding technique is very popular for coding both monochrome and color images. This technique uses Max's method of optimum quantizer design, assuming Gaussian DC and AC coefficient probability density functions. Transform sub-blocks of the original image are assigned to one of four classes on the basis of sub-block AC energy. The variance of each coefficient is calculated and used in a bit allocation technique in order to determine a bit assignment map for each class. The transform coefficients are normalized by their corresponding variances to achieve unit variance prior to quantization.

The basic Chen-Smith approach is designed to achieve a given compression no matter what image is to be compressed. This means that, for a given compression, the image quality of more complex

images is poorer than that of less complex images. The image-dependent variation compensates for this somewhat by analyzing all of the AC energies of sub-blocks in the image in order to allocate more bits to busy sub-blocks. More bits are allocated per sub-block to images with a high amount of activity, and fewer bits per sub-block are allocated to images with a low amount of activity in order to achieve higher compression for images with low activity, and better image quality for images with high activity.

2.3 Selection of Test Documents

The test documents employed in the simulations were selected based on several factors, including image quality, availability, and feature content. Four gray scale images were chosen as the test image set; this set consists of the standard gray scale images developed by Delta Information Systems for the NCS in a previous study (Ref. 5). The standard gray scale images were selected based on a set of characteristics that was designed to thoroughly test various gray scale transmission techniques.

Beyond the advantages these images provide in terms of image quality and availability, each image was selected because it contained several distinctive features that would aid in the subjective evaluation of the output images. The IEEE image is representative of an identification card, combining both photographic and textual information, and includes a high

contrast wedge that aids in the evaluation of an algorithm's effect on resolution. The house and sky image contains large areas of gradually changing gray scale, several areas of varying texture, and various horizontal, vertical, and diagonal lines. The house with trees image is similar, but also contains high detail regions. The aerial photograph is a low contrast image of high detail and relatively low resolution.

3.0 RESULTS

3.1 Compression Statistics

The results achieved in the simulations performed to determine the relative performances of the dither coding algorithms evaluated in this study are summarized in Table 3.1. The information in the table is organized as follows:

- Column 1: Image Name, where IEEE is the IEEE test chart image, HSSK is the house and sky image, HSTR is the house with trees image, and AERO is the aerial photograph image.
- Column 2: Compression Technique indicates which type of dither coding algorithm was employed (i.e. pre-transmission or post-transmission).
- Column 3: Dithering Algorithm indicates which dithering approach was employed in the simulation (Ad. Clump refers to the adaptive clumped dithering technique).
- Column 4: Additional Compression Processing indicates the additional steps, if any, employed to perform the simulation:
 - Straight indicates that no additional steps were employed.
 - Plane sep. indicates that the clump dithered or adaptive clumped dithered image was separated into clump planes prior to being run-length encoded.
 - Bit Reord. indicates that the ordered dithering was performed adaptively and that the dithered image was reordered prior to being run-length encoded.
 - Bit Intrl. indicates that the ordered dithering was performed adaptively and that the dithered image was interleaved prior to being run-length encoded.

Table 3.1 - Compression Results - Page 1 of 2

Image Name	Compression Technique	Dithering Algorithm	Additional Compression Processing	Number of Compressed Bits/Image	Compressed Bits/Pixel
I E E E	Pre-trans- mission Dithering	Ad. Clump	Straight	491457	0.66
			Plane Sep.	427650	0.57
		Clumped	Straight	521675	0.70
			Plane Sep.	535711	0.72
		Ordered	Straight	700877	0.94
			Bit Reord.	336378	0.45
			Bit Intrl.	220861	0.30
	DPCM	Ad. Clump	Straight	983635	1.32
			Subsampled	547218	0.73
	Transform	Ad. Clump	Ad. Zonal	(456032)	0.62
			Chen-Smith	(773765)	1.05

H S S K	Pre-trans- mission Dithering	Ad. Clump	Straight	760923	0.98
			Plane Sep.	303295	0.39
		Clumped	Straight	765399	0.98
			Plane Sep.	314515	0.40
		Ordered	Straight	974499	1.25
			Bit Reord.	369056	0.47
			Bit Intrl.	158911	0.20
	DPCM	Ad. Clump	Straight	991022	1.27
			Subsampled	543871	0.70
	Transform	Ad. Clump	Ad. Zonal	(284128)	0.38
			Chen-Smith	(675307)	0.89

Table 3.1 - Compression Results - Page 2 of 2

Image Name	Compression Technique	Dithering Algorithm	Additional Compression Processing	Number of Compressed Bits/Image	Compressed Bits/Pixel
H S T R	Pre-trans- mission Dithering	Ad. Clump	Straight	622308	0.81
			Plane Sep.	528011	0.69
		Clumped	Straight	628036	0.81
			Plane Sep.	509711	0.66
		Ordered	Straight	763803	0.99
			Bit Reord.	400394	0.52
			Bit Intrl.	298610	0.39
	DPCM	Ad. Clump	Straight	1325341	1.72
			Subsampled	770661	1.00
	Transform	Ad. Clump	Ad. Zonal	(562408)	0.74
			Chen-Smith	(753707)	1.00

A E R O	Pre-trans- mission Dithering	Ad. Clump	Straight	641243	0.89
			Plane Sep.	530291	0.74
		Clumped	Straight	644250	0.89
			Plane Sep.	552482	0.77
		Ordered	Straight	793796	1.10
			Bit Reord.	373536	0.52
			Bit Intrl.	223559	0.31
	DPCM	Ad. Clump	Straight	1018555	1.41
			Subsampled	626229	0.87
	Transform	Ad. Clump	Ad. Zonal	(479744)	0.68
			Chen-Smith	(817995)	1.16

- Subsampled indicates that the DPCM encoded image was subsampled at the encoder and interpolated at the decoder prior to dithering.
- Ad. Zonal indicates that the adaptive zonal transform coding technique was employed in the simulation.
- Chen-Smith indicates that the Chen-Smith transform coding technique was employed in the simulation.

Column 5: Number of Compressed Bits/Image indicates the number of bits, including overhead data, required to transmit the compressed image (the compressed number of bits/image reported for the transform coding simulations are enclosed in parentheses to indicate that the image area compressed was slightly smaller than that in the other simulations).

Column 6: Compressed Number Bits/Pixel is a measure of the relative performance of the dither coding algorithms in terms of compression.

The pre-transmission dither coding algorithms were simulated using a combination of pre-existing and newly developed software. The clumped dithering software module was developed for an earlier study (Ref. 3), as were the Group 4 encoding and decoding software modules. The adaptive clumped dithering and clump plane separation software modules were designed and developed by Delta Information Systems (DIS) for this study. The ordered dithering, adaptive bit reordering, and adaptive bit interleaving software modules were developed by DIS for this study and were based on a contribution to CCITT Study Group VIII (Ref. 4).

Two DPCM compression algorithms were simulated in a study previously performed by Delta Information Systems (Ref. 1). Of the two, conditional DPCM was selected as an example of a gray scale compression technique that could be used as part of a post-

transmission dither coding algorithm. Conditional DPCM offers a good combination of low algorithm complexity, good compression, and excellent image quality. Conditional DPCM employs a three-neighbor gray level value predictor, a non-linear three-bit quantizer, Huffman entropy coding, and an optional staggered horizontal sub-sampler and corresponding interpolator. In order to determine the effects of subsampling/interpolation on compression and dithered image quality, simulations were performed both with and without subsampling.

Four transform coding algorithms were simulated in a study previously performed by Delta Information Systems (Ref. 2). Of the four, two were selected as examples of gray scale compression techniques that could be used as part of a post-transmission dither coding algorithm. Adaptive zonal transform coding offers a combination of low algorithm complexity, good compression, and good image quality. The image dependent Chen-Smith transform coding algorithm offers a combination of moderate complexity, excellent compression, and very good image quality.

Each transform coding algorithm has adjustable parameters that can be varied in order to select a target compression. In the adaptive zonal coding algorithm simulations, the cutoff threshold for the elimination of insignificant coefficients prior to quantization was set to $CO = 1.5$ in order to produce compression results comparable to those achieved in the DPCM simulations. In the image dependent Chen-Smith algorithm simulations, the average number of bits/pixel over the four bit

map classifications was set to $BM = 1.0$ in order to produce compression comparable to that achieved by the DPCM simulations.

The adjustable parameters employed in the transform coding simulations were selected to achieve compressions comparable to those achieved for the DPCM simulations in order to facilitate image quality comparisons between the two post-transmission dithering techniques. Because the compression achieved by the transform coding algorithms is selectable, transform coding can outperform the other dither coding techniques in terms of compression. Therefore, the comparisons made between transform coding and the other techniques were made based on image quality at comparable achieved compressions.

3.2 Output Images

Before the image quality of the dither coding techniques can be evaluated, a discussion of the sources of distortion caused by the algorithms is in order. The image distortion caused by the pre-transmission algorithms is produced by the dithering process employed. The repetition of the dithering matrices produces visually apparent patterns, and contouring is produced in smooth areas of the image where slowly changing gray levels are present. The images produced by the post-transmission dither coding techniques contain distortion from the quantization process associated with the DPCM and transform coding algorithms in addition to the distortion caused by the dithering process.

Distortion due to DPCM coding is represented by a blurring, or "graying", of sharp gray scale edges in the image. Distortion due to transform coding is represented by a "blocking" effect, in which the contents of a decoded image sub-block is markedly different from neighboring sub-blocks.

The image rearrangement steps associated with the pre-transmission dithering techniques do not contribute to the distortion of the output images. They are designed to increase the compressibility of the dithered images without affecting image quality. The adaptive pre-transmission dithering techniques improve both compression and output image quality by processing gray scale information and bi-level information independently. Figures 3.1 through 3.7 illustrate the rearranged images resulting from the various pre-transmission dithering techniques, as they appear prior to the Group 4 encoding step.

Figures 3.1 and 3.2 are examples of the X and Y images, respectively, produced by the adaptive clumped dithering with clump plane separation algorithm. Image X contains all of the low distinction blocks in the image, in which the pixels have been thresholded with the clumped dither matrix thresholds and then rearranged into clump planes. Image Y contains all of the high distinction blocks in the image, in which the pixels have been thresholded with a single user-specified threshold. Figure 3.3 is an example of the intermediate image produced by the clump plane separation algorithm.

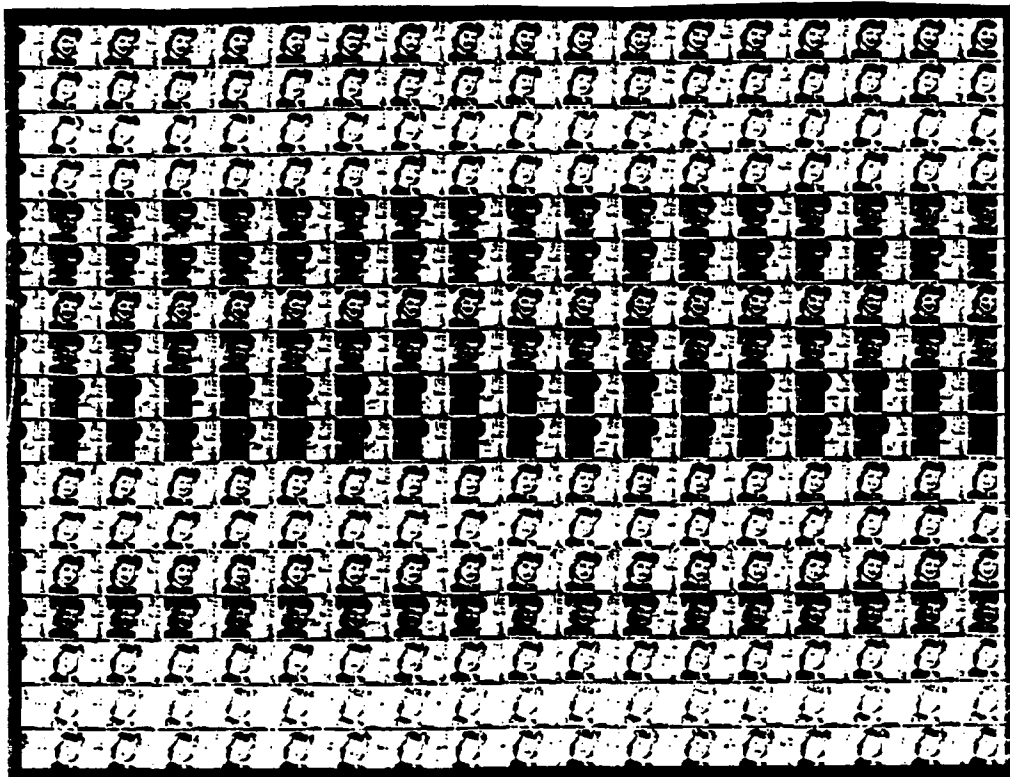


Figure 3.1 - Adaptive Clumped Dithering with Clump Plane Separation, Image X

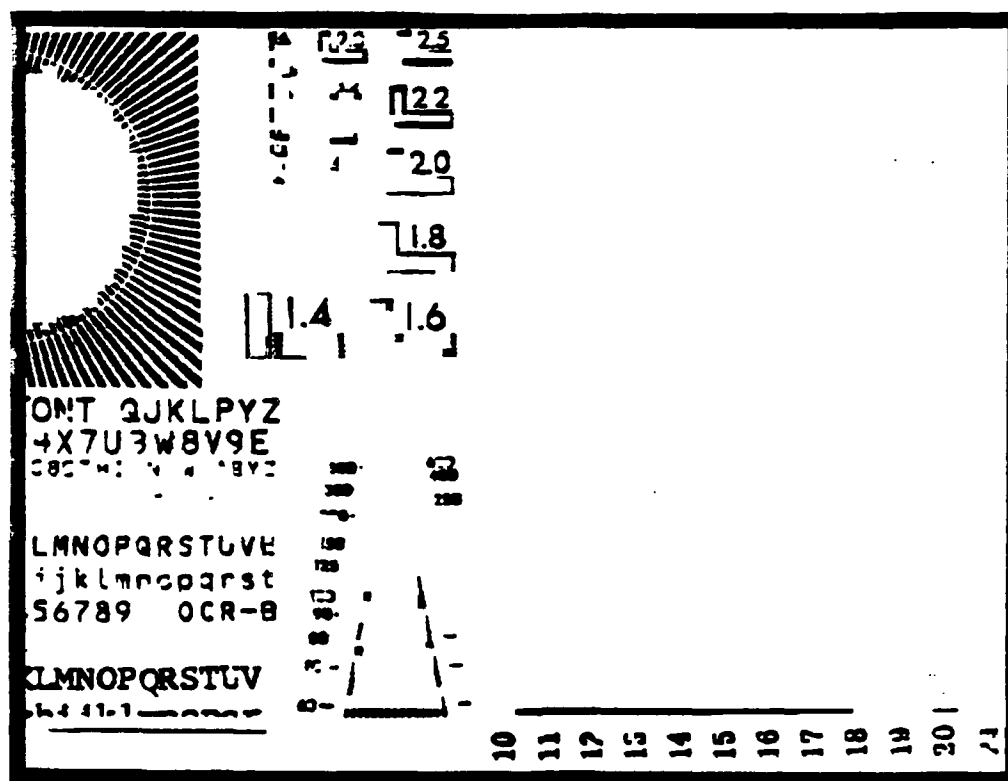


Figure 3.2 - Adaptive Clumped Dithering with Clump Plane Separation, Image Y

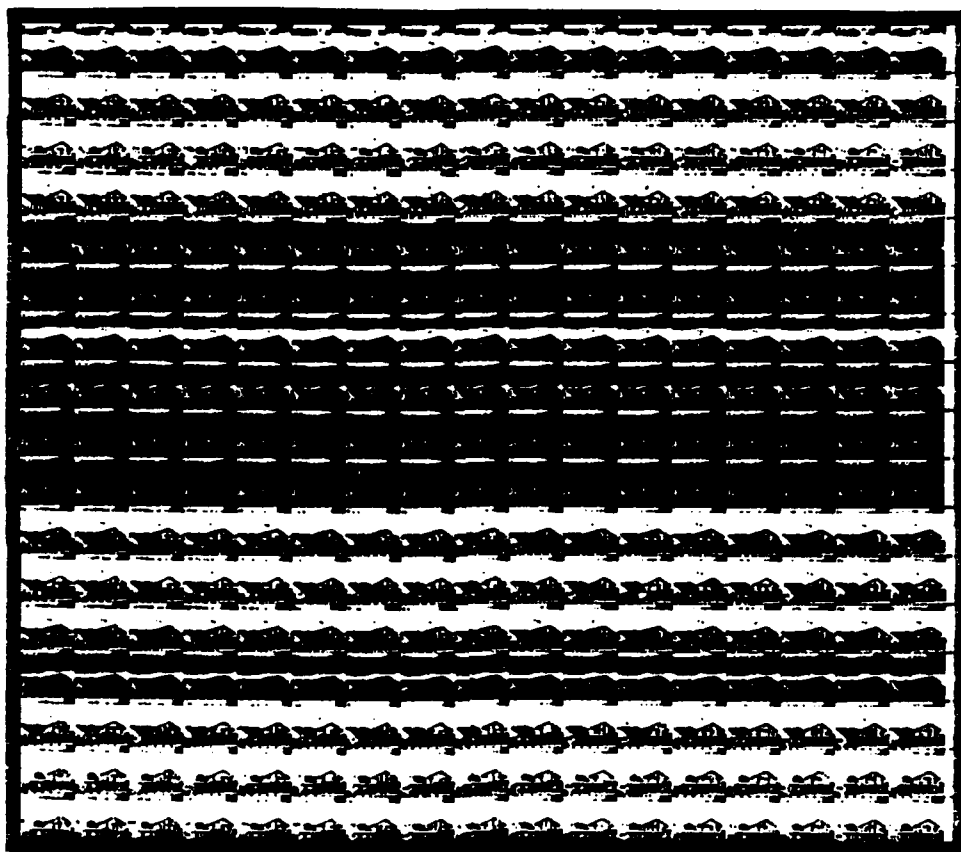


Figure 3.3 - Clumped Dithering with Clump Plane Separation

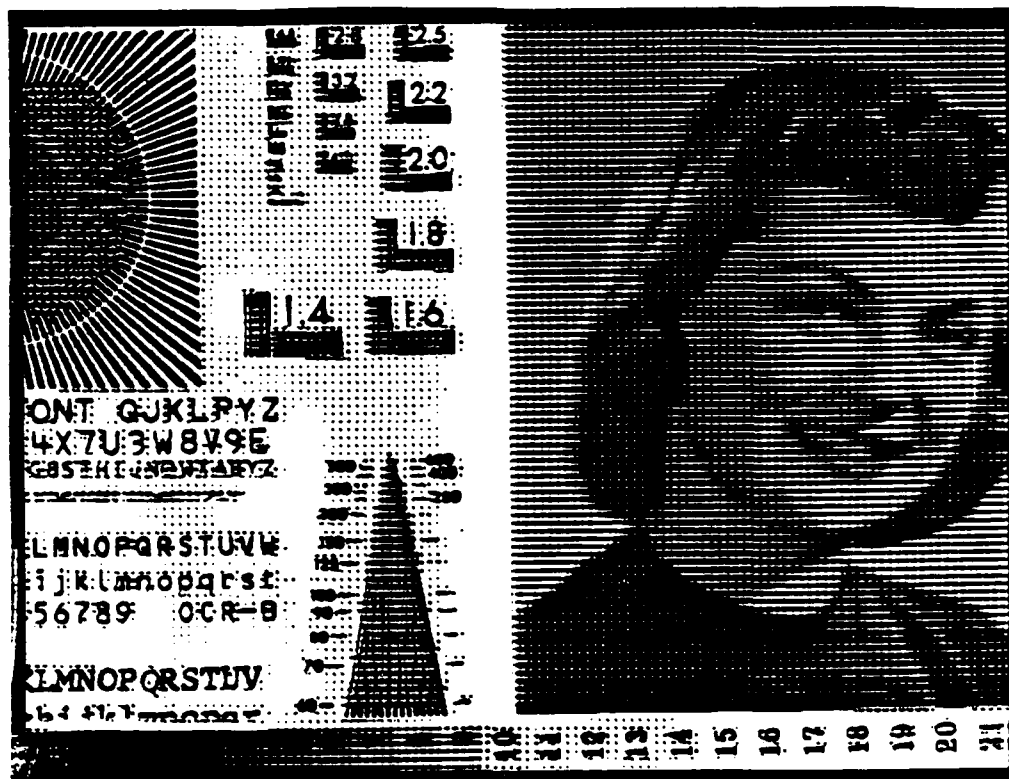


Figure 3.4 - Ordered Dithering with Adaptive Bit Reordering,
Dithered Image



Figure 3.5 - Ordered Dithering with Adaptive Bit Reordering,
Block Identification Image

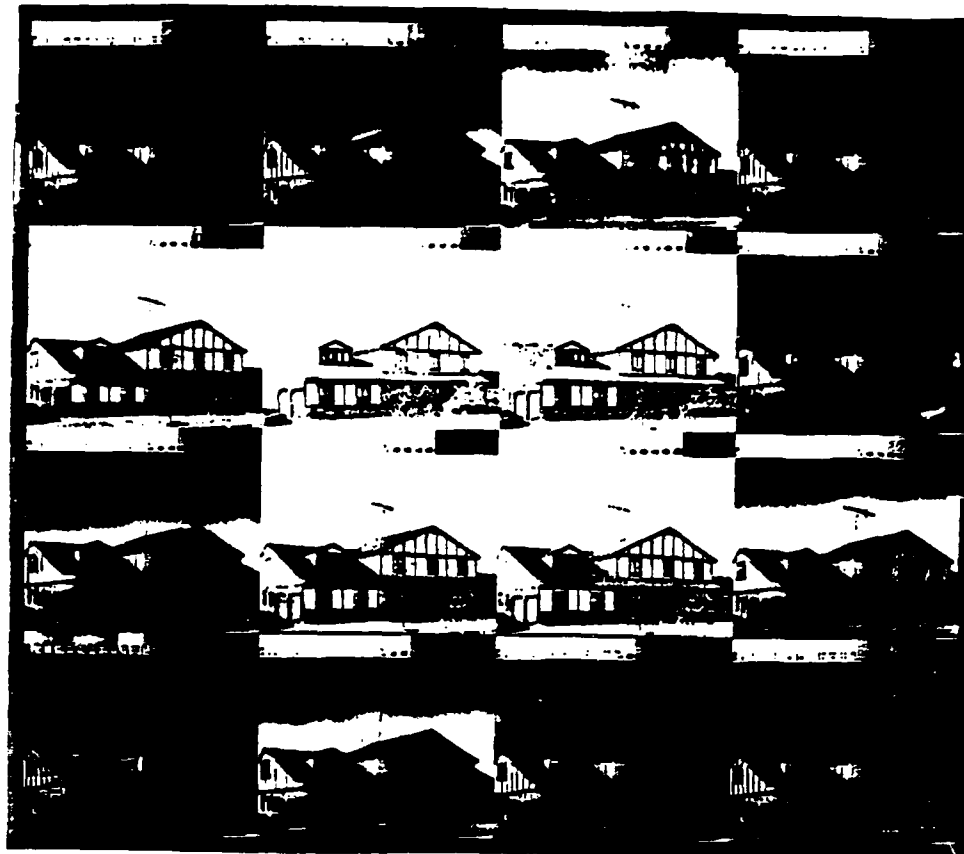


Figure 3.6 - Ordered Dithering with Adaptive Bit Interleaving,
Image X

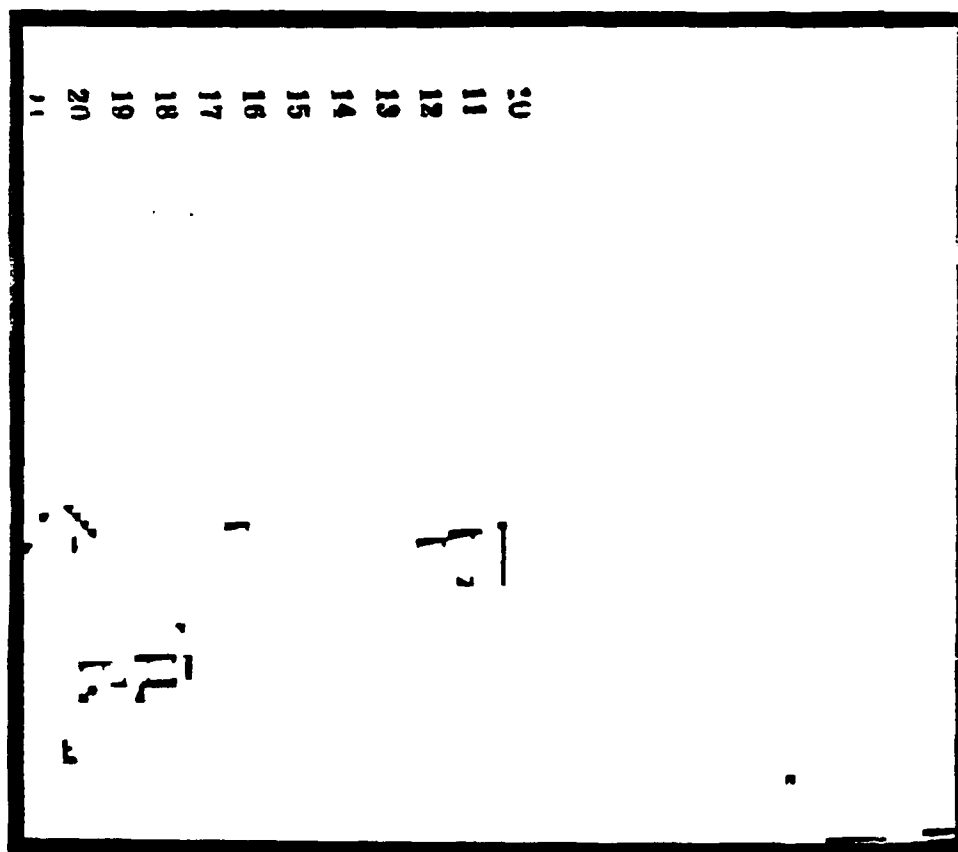


Figure 3.7 - Ordered Dithering with Adaptive Bit Interleaving,
Image Y

Figures 3.4 and 3.5 are examples of the dithered and block identification images, respectively, produced by the adaptive ordered dithering with bit reordering algorithm. The dithered image contains all of the blocks in the image, both low distinction and high distinction. The block identification image contains the corresponding block identification bits; these bits identify which blocks in the image have been reordered. Figures 3.6 and 3.7 are examples of the X and Y images, respectively, produced by the adaptive ordered dithering with bit interleaving algorithm. Image X contains all of the low distinction blocks in the image, in which the pixels have been thresholded with the ordered dither matrix thresholds and then rearranged over the entire image. Image Y contains all of the high distinction blocks in the image, in which the pixels have been thresholded with a single user-specified threshold.

Table 3.2 is a list of the output images presented in Figures 3.8 through 3.39. Each figure represents the output image of one or two of the simulations performed in this study. Because the clump plane separation step has no effect on image quality, clumped dithering and clumped dithering with clump plane separation produce identical output images; therefore, only one image, referred to in Table 3.2 as "Pre-transmission, Clumped," is employed (for each test image) to represent the two simulation runs. The same holds true for adaptive clumped dithering and adaptive clumped dithering with clump plane separation (referred to in Table 3.2 as "Pre-transmission, Ad. Clumped"). The

Table 3.2 - Output Images - Page 1 of 2

Image Name	Compression Technique	Dithering/Compression Algorithm	Figure Number
I E E E	Pre-transmission Dithering	Ad. Clumped	3.8
		Clumped	3.9
		Ordered	3.10
		Ad. Ordered	3.11
	DPCM	Straight	3.12
		Subsampled	3.13
	Transform	Ad. Zonal	3.14
		Chen-Smith	3.15

H S S K	Pre-transmission Dithering	Ad. Clumped	3.16
		Clumped	3.17
		Ordered	3.18
		Ad. Ordered	3.19
	DPCM	Straight	3.20
		Subsampled	3.21
	Transform	Ad. Zonal	3.22
		Chen-Smith	3.23

Table 3.2 - Output Images - Page 2 of 2

Image Name	Compression Technique	Dithering/Compression Algorithm	Figure Number
H S T R	Pre-trans- mission Dithering	Ad. Clumped	3.24
		Clumped	3.25
		Ordered	3.26
		Ad. Ordered	3.27
	DPCM	Straight	3.28
		Subsampled	3.29
	Transform	Ad. Zonal	3.30
		Chen-Smith	3.31

A E R O	Pre-trans- mission Dithering	Ad. Clumped	3.32
		Clumped	3.33
		Ordered	3.34
		Ad. Ordered	3.35
	DPCM	Straight	3.36
		Subsampled	3.37
	Transform	Ad. Zonal	3.38
		Chen-Smith	3.39

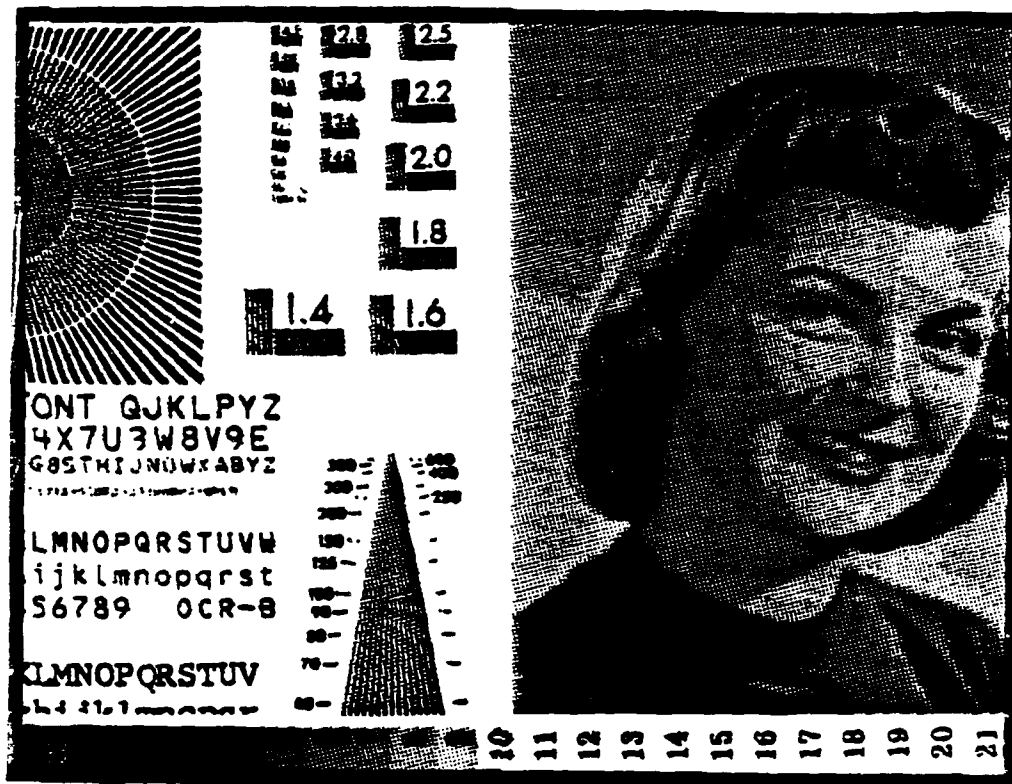


Figure 3.8 - Adaptive Clumped Dithered IEEE Image

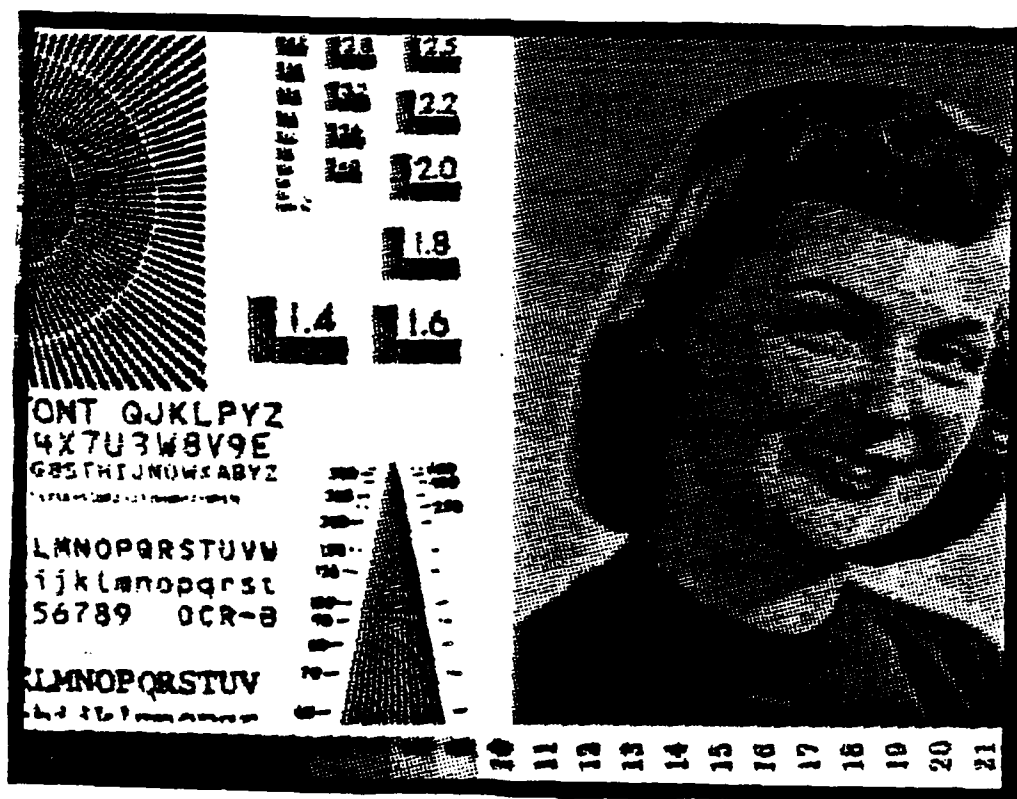


Figure 3.9 - Clumped Dithered IEEE Image



Figure 3.10 - Ordered Dithered IEEE Image

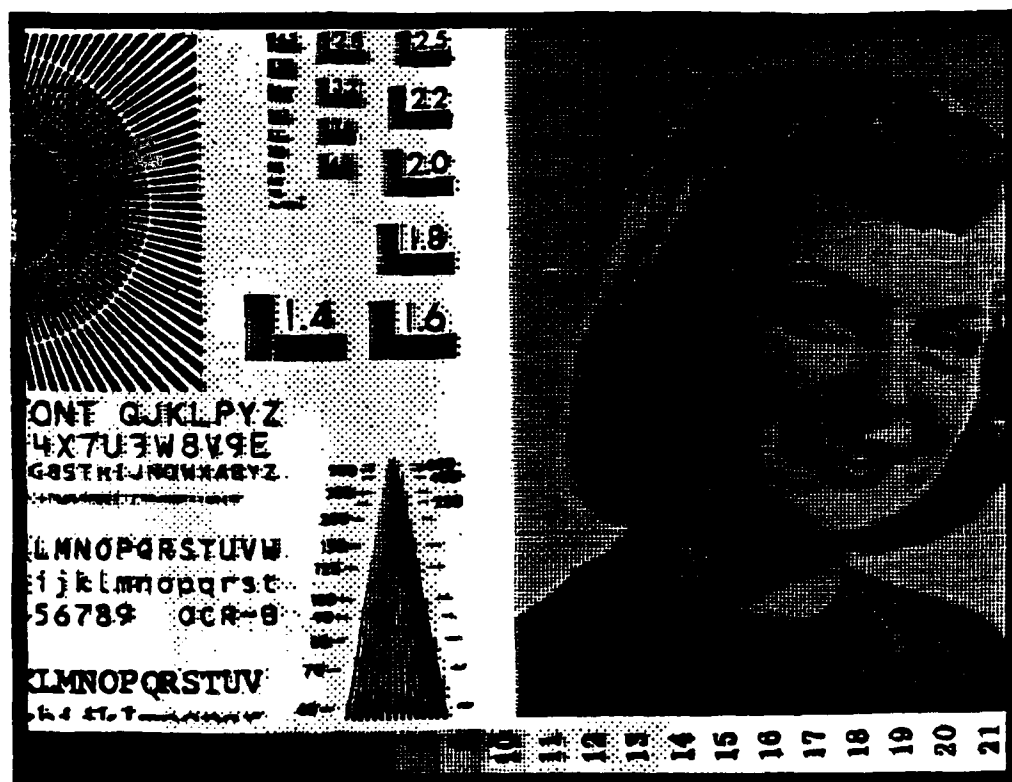


Figure 3.11 - Adaptive Ordered Dithered IEEE Image

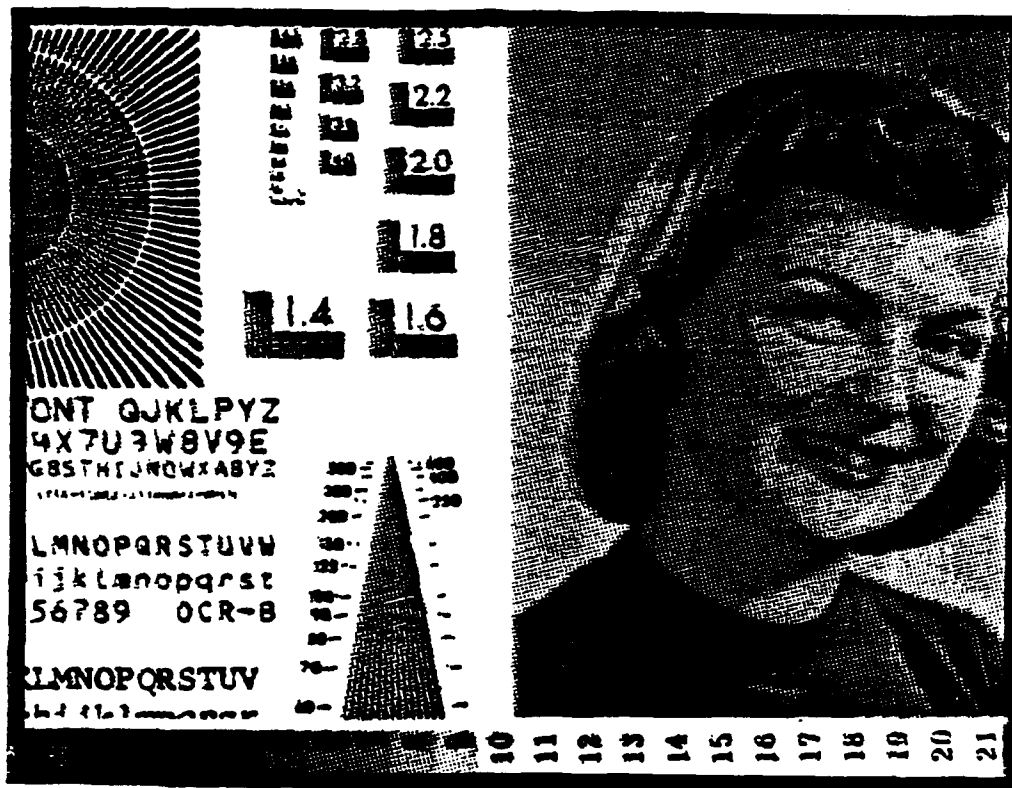


Figure 3.12 - Straight DPCM Encoded IEEE Image

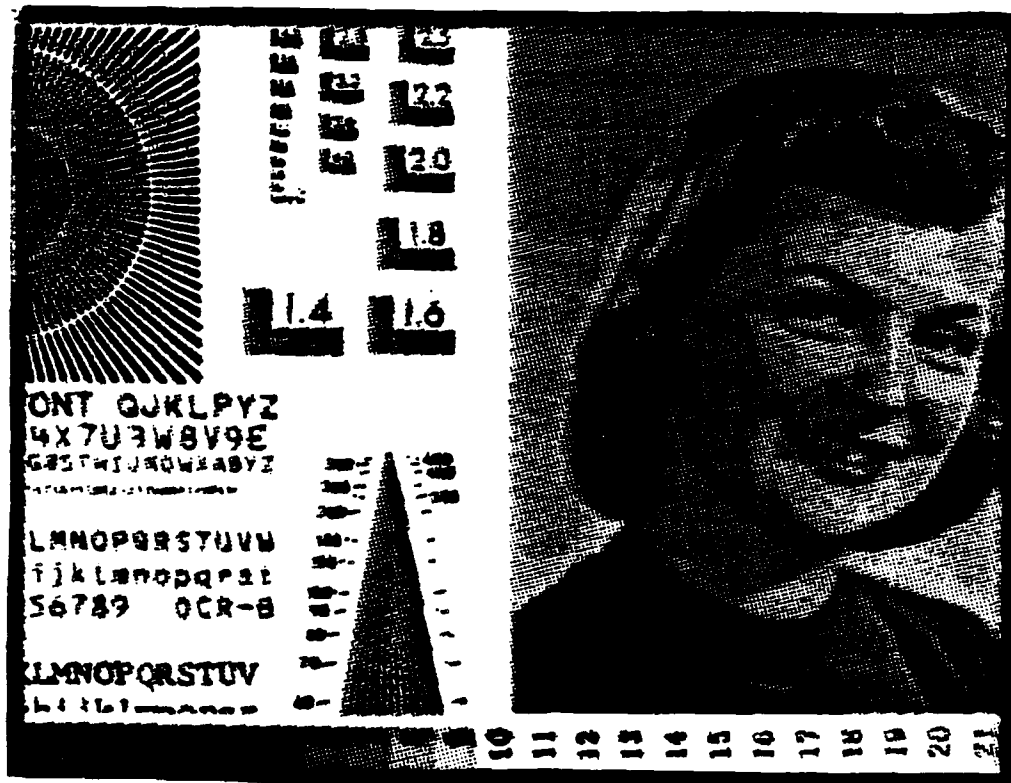


Figure 3.13 - Subsampled DPCM Encoded IEEE Image



Figure 3.14 - Adaptive Zonal Encoded IEEE Image



Figure 3.15 - Image Dependent Chen-Smith Encoded IEEE Image

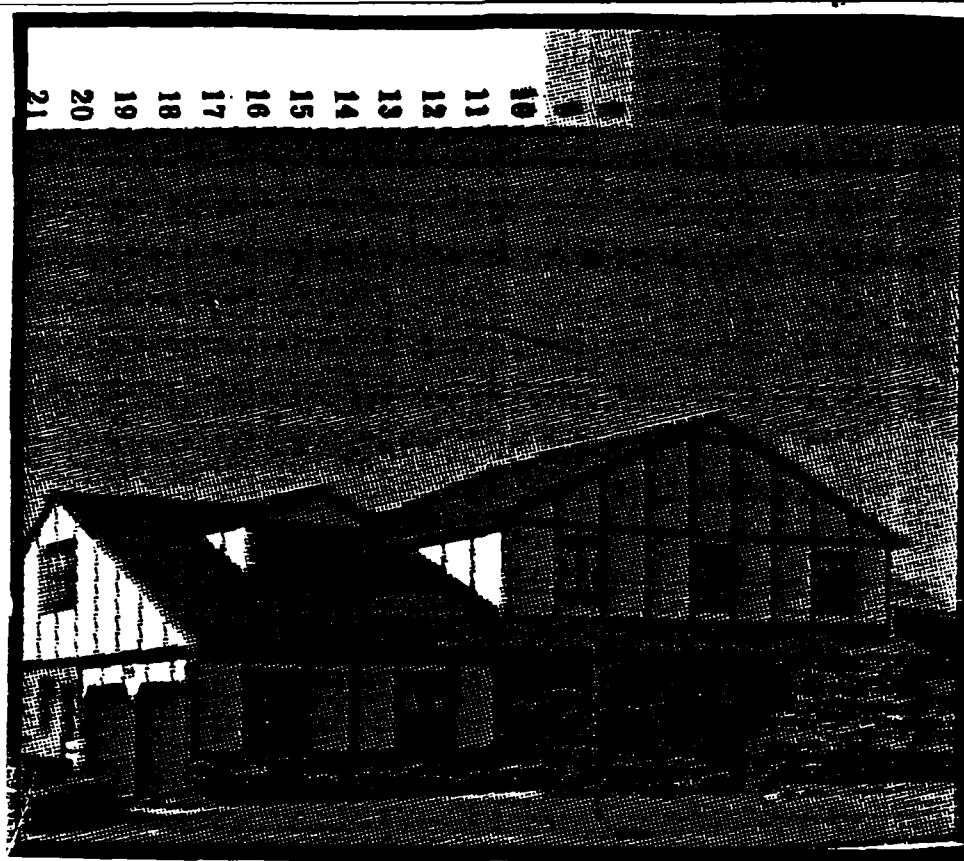


Figure 3.16 - Adaptive Clumped Dithered House and Sky Image



Figure 3.17 - Clumped Dithered House and Sky Image

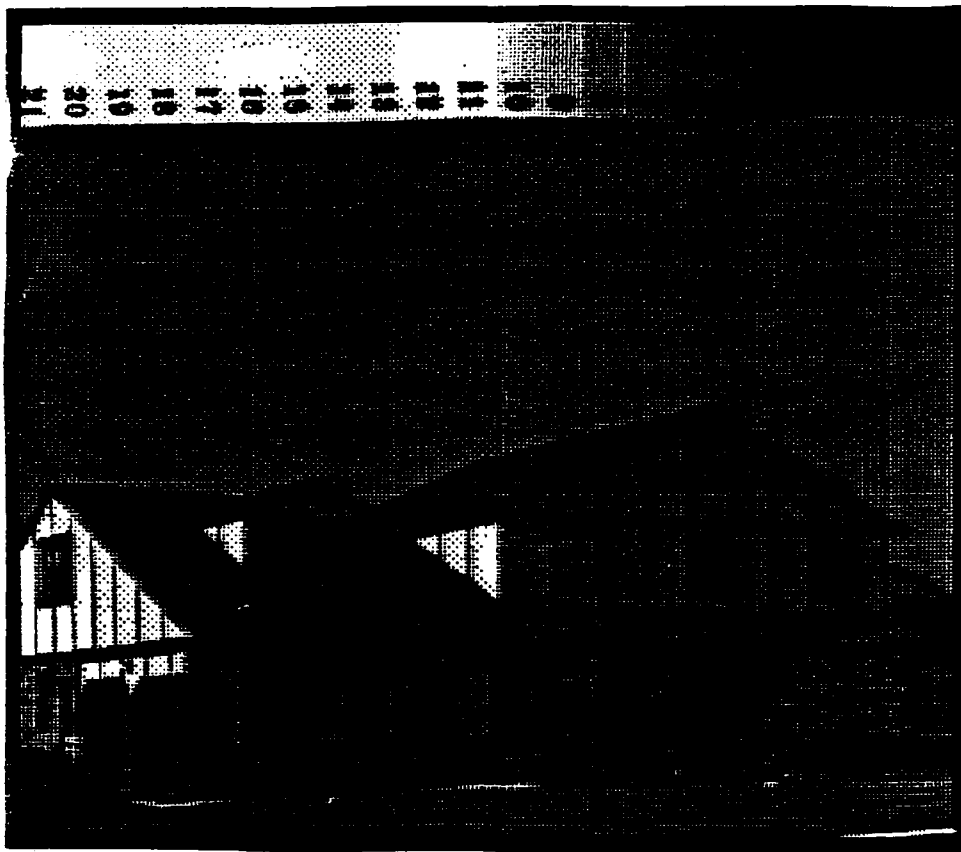


Figure 3.18 - Ordered Dithered House and Sky Image

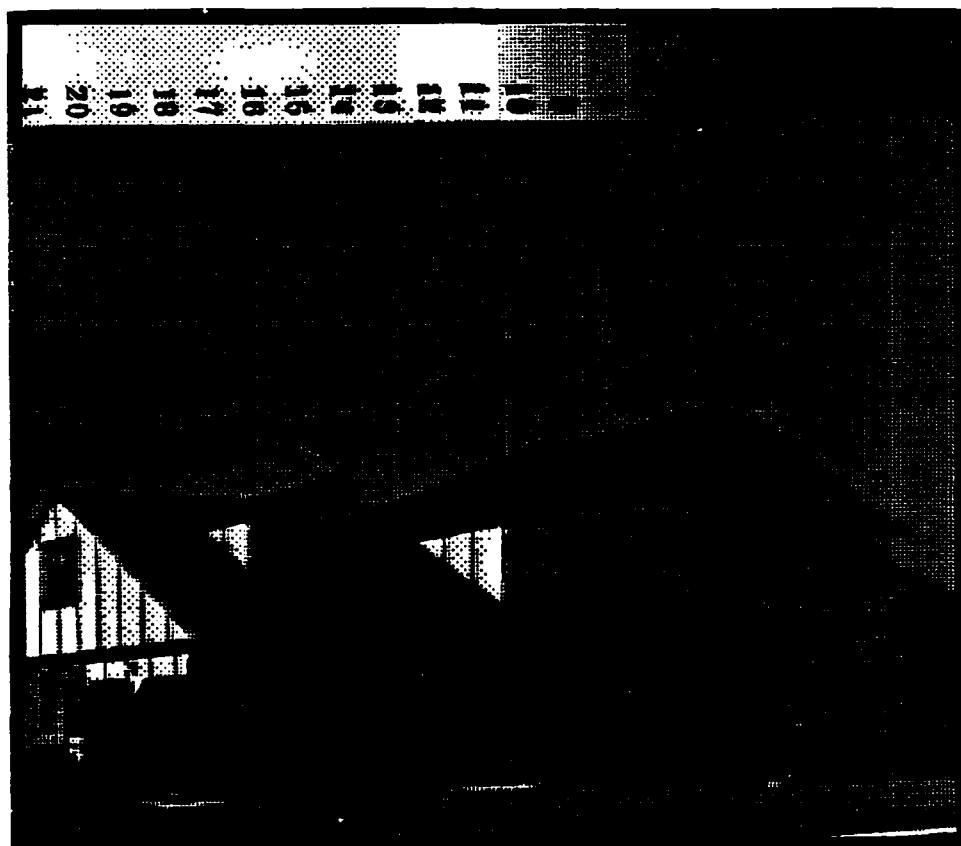


Figure 3.19 - Adaptive Ordered Dithered House and Sky Image

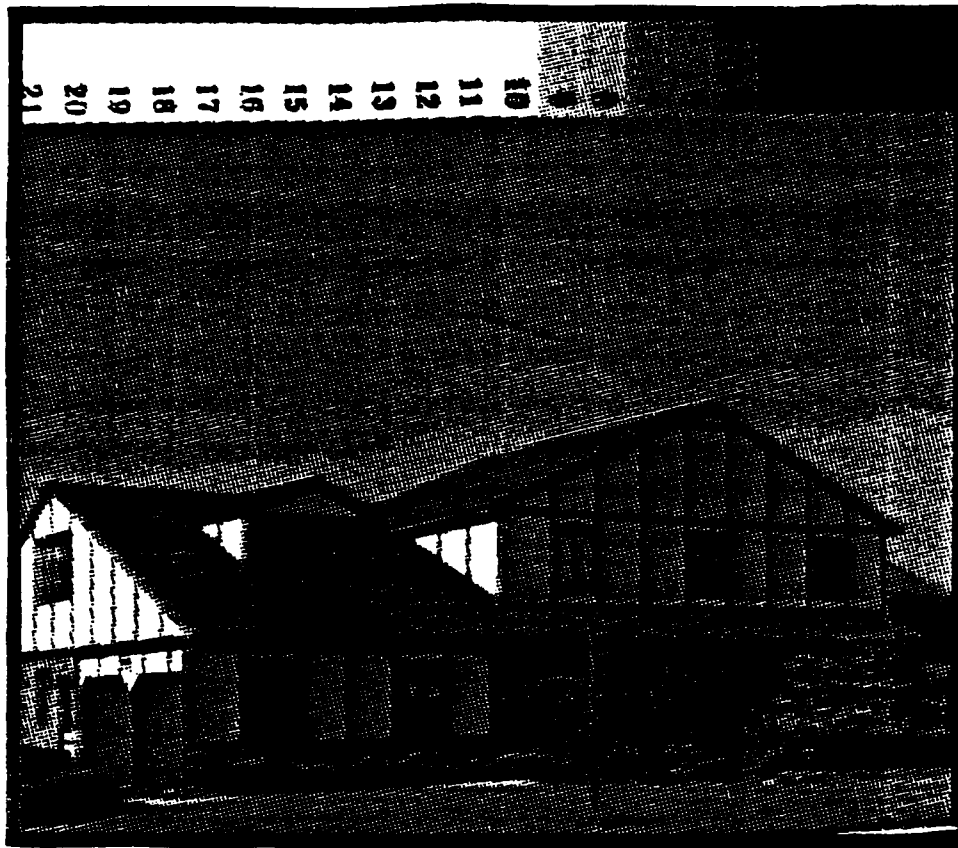


Figure 3.20 - Straight DPCM Encoded House and Sky Image



Figure 3.21 - Subsampled DPCM Encoded House and Sky Image

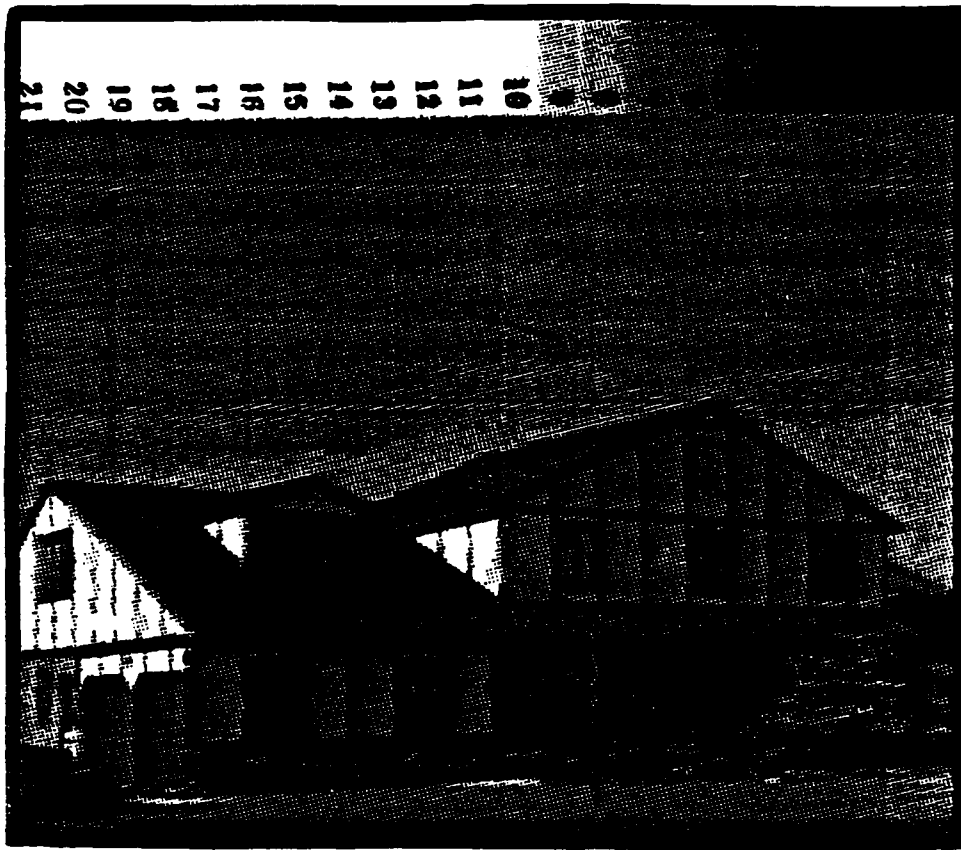


Figure 3.22 - Adaptive Zonal Encoded House and Sky Image

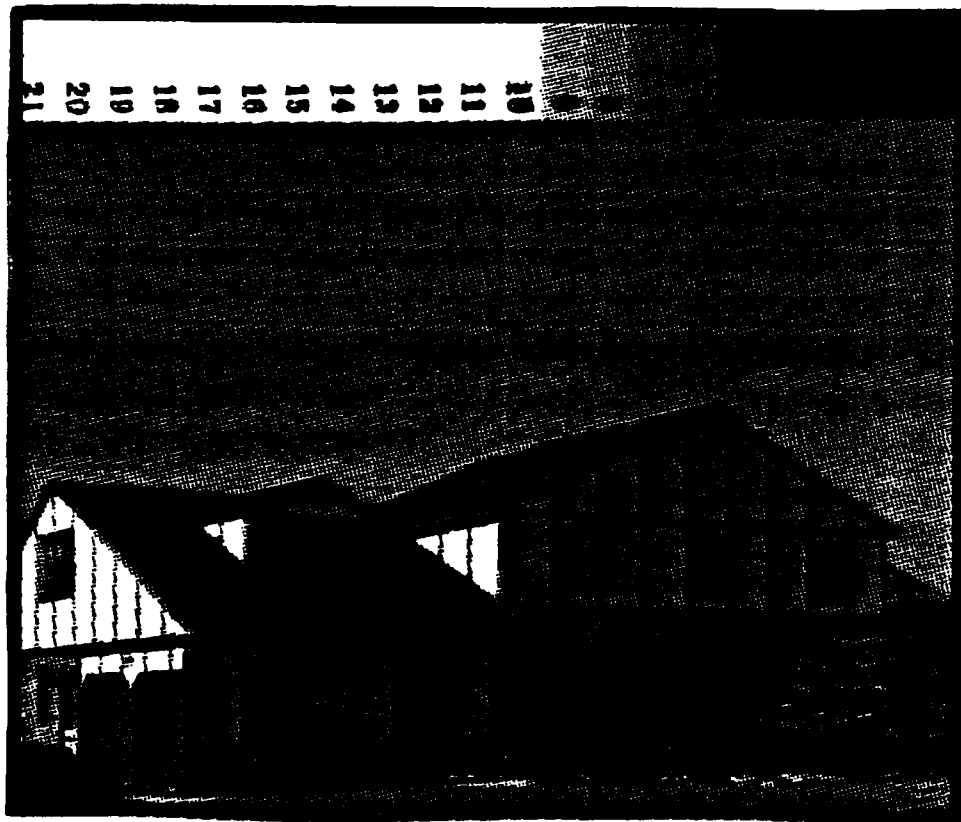


Figure 3.23 - Image Dependent Chen-Smith Encoded House and Sky Image



Figure 3.24 - Adaptive Clumped Dithered House with Trees Image

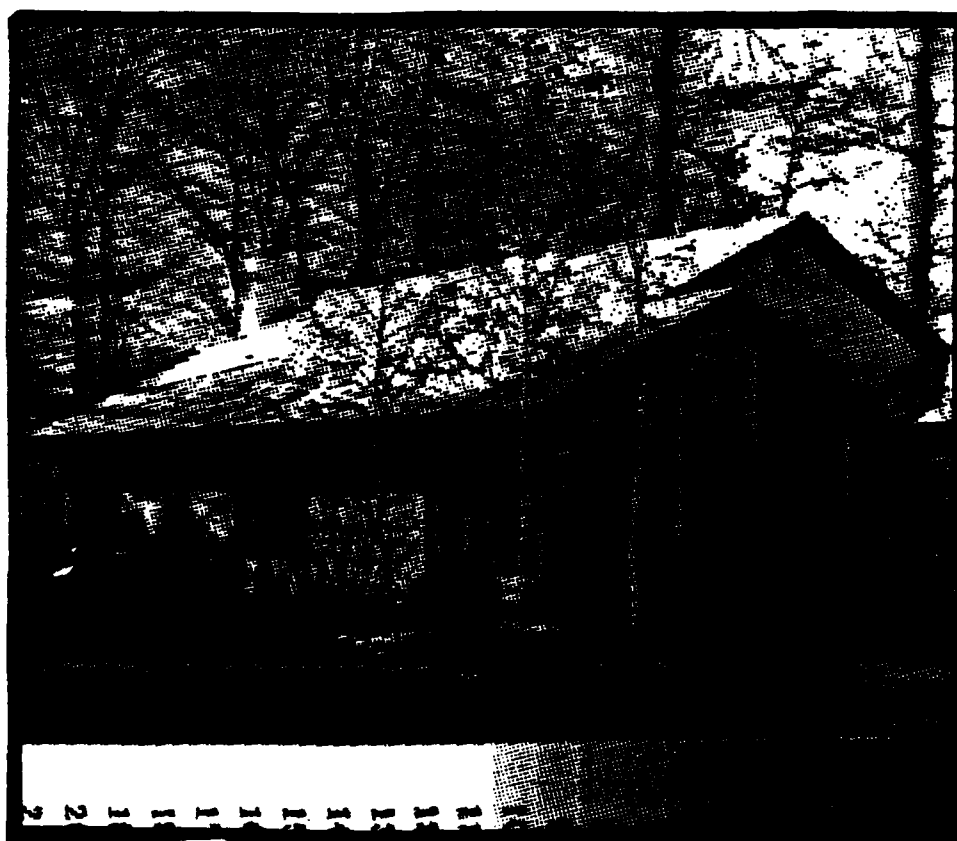


Figure 3.25 - Clumped Dithered House with Trees Image



Figure 3.26 - Ordered Dithered House with Trees Image

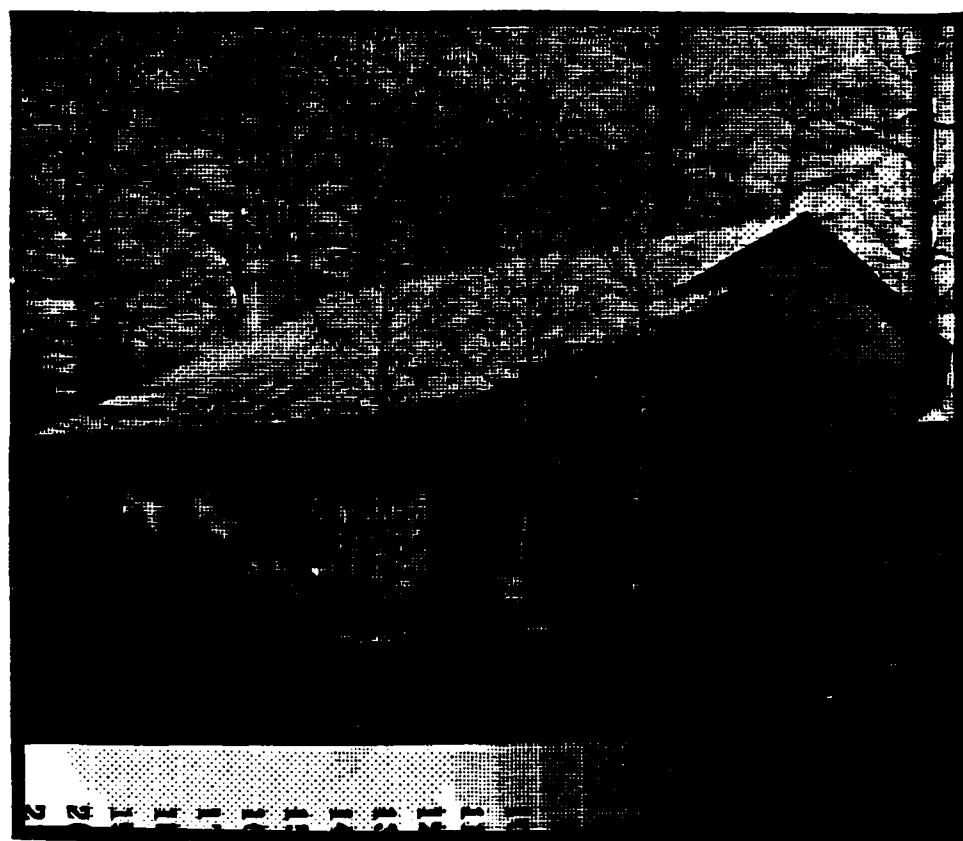


Figure 3.27 - Adaptive Ordered Dithered House with Trees Image



Figure 3.28 - Straight DPCM Encoded House with Trees Image

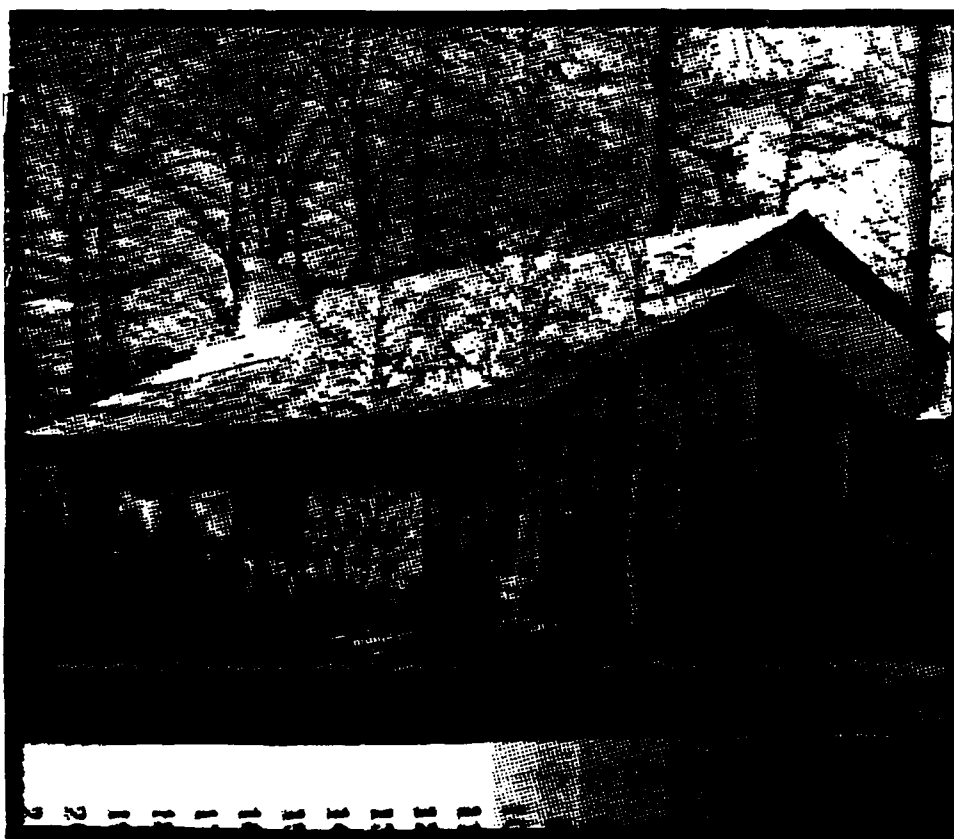


Figure 3.29 - Subsampled DPCM Encoded House with Trees Image



Figure 3.30 - Adaptive Zonal Encoded House with Trees Image

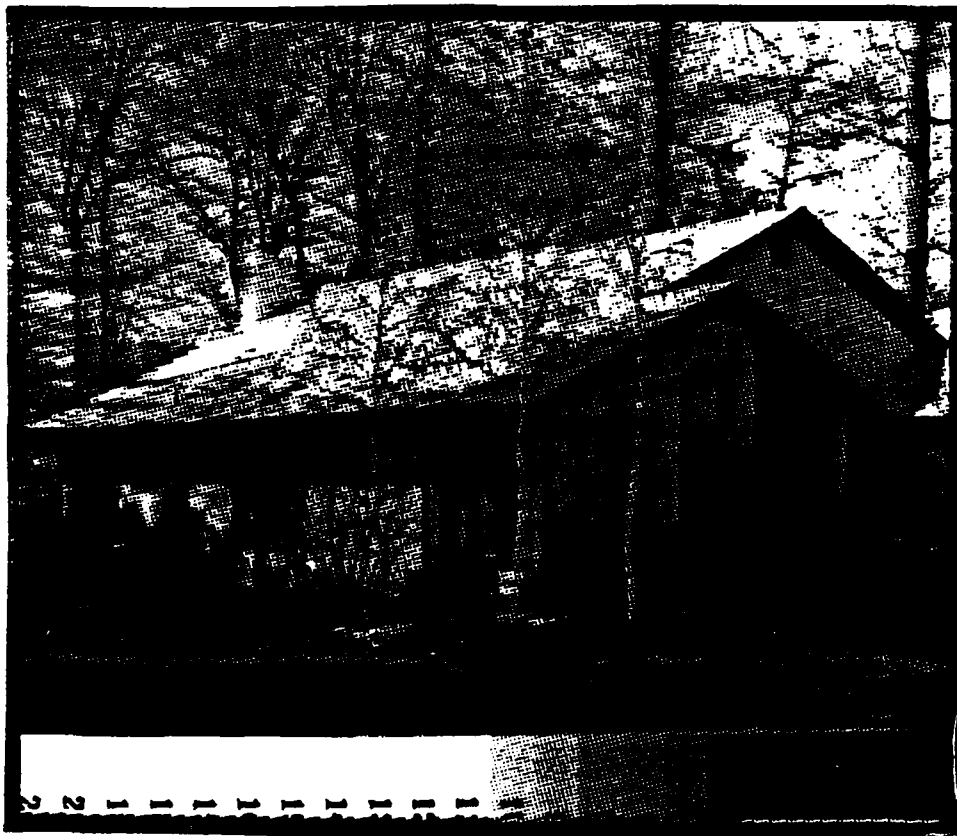


Figure 3.31 - Image Dependent Chen-Smith Encoded House with Trees Image

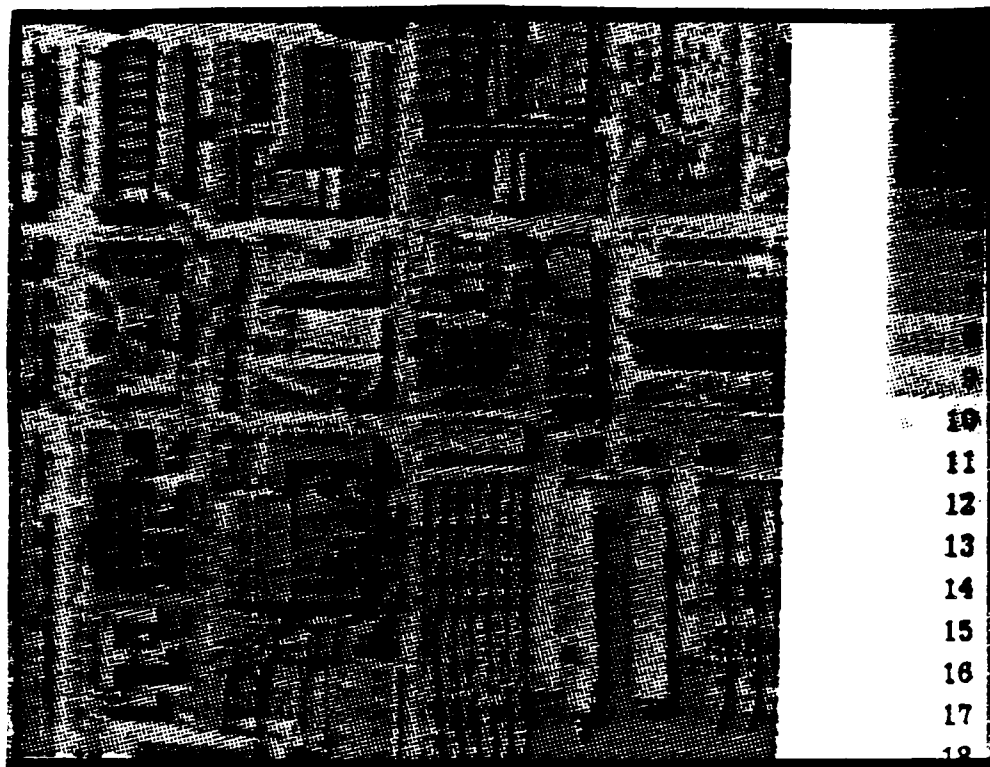


Figure 3.32 - Adaptive Clumped Dithered Aerial Photo

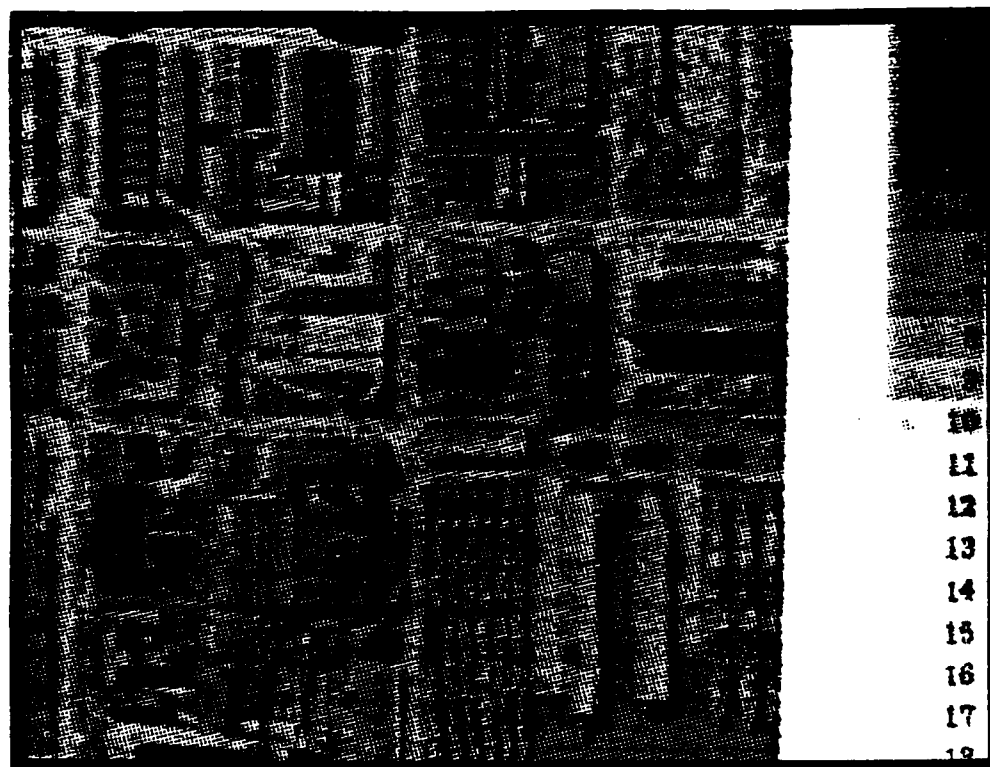


Figure 3.33 - Clumped Dithered Aerial Photo

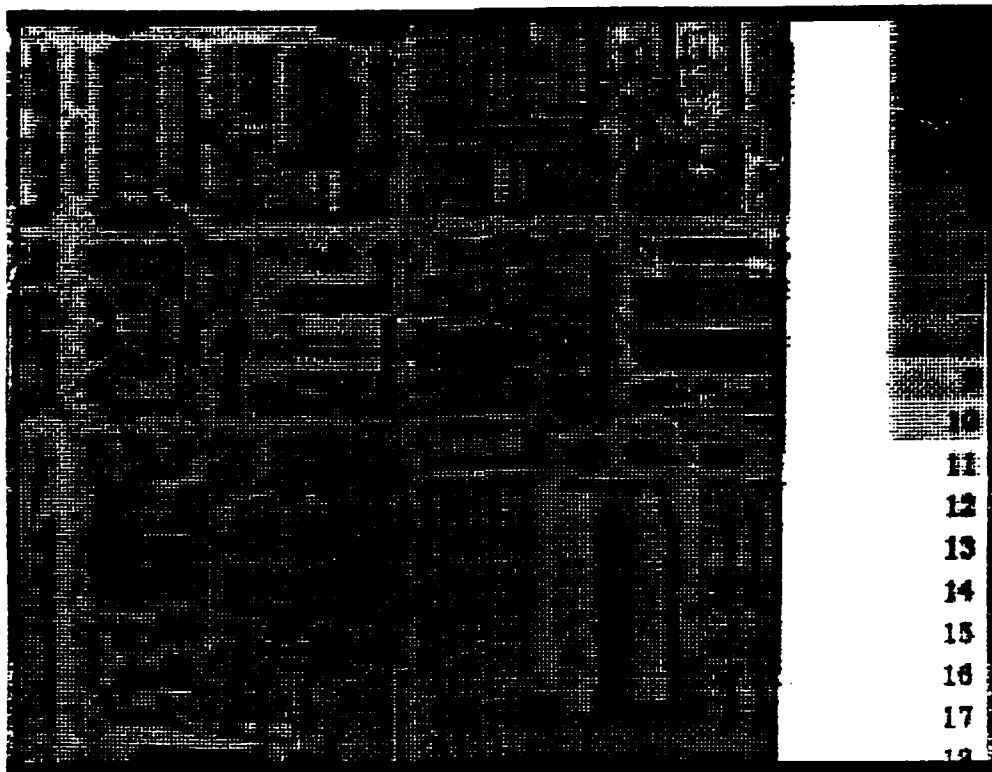


Figure 3.34 - Ordered Dithered Aerial Photo

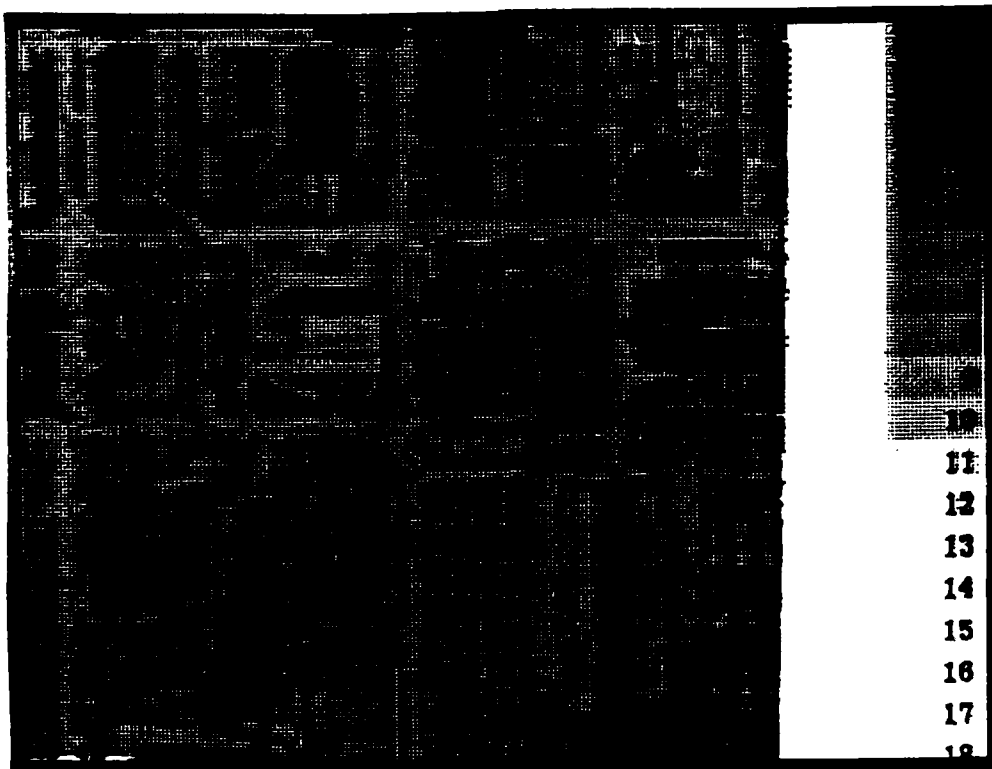


Figure 3.35 - Adaptive Ordered Dithered Aerial Photo

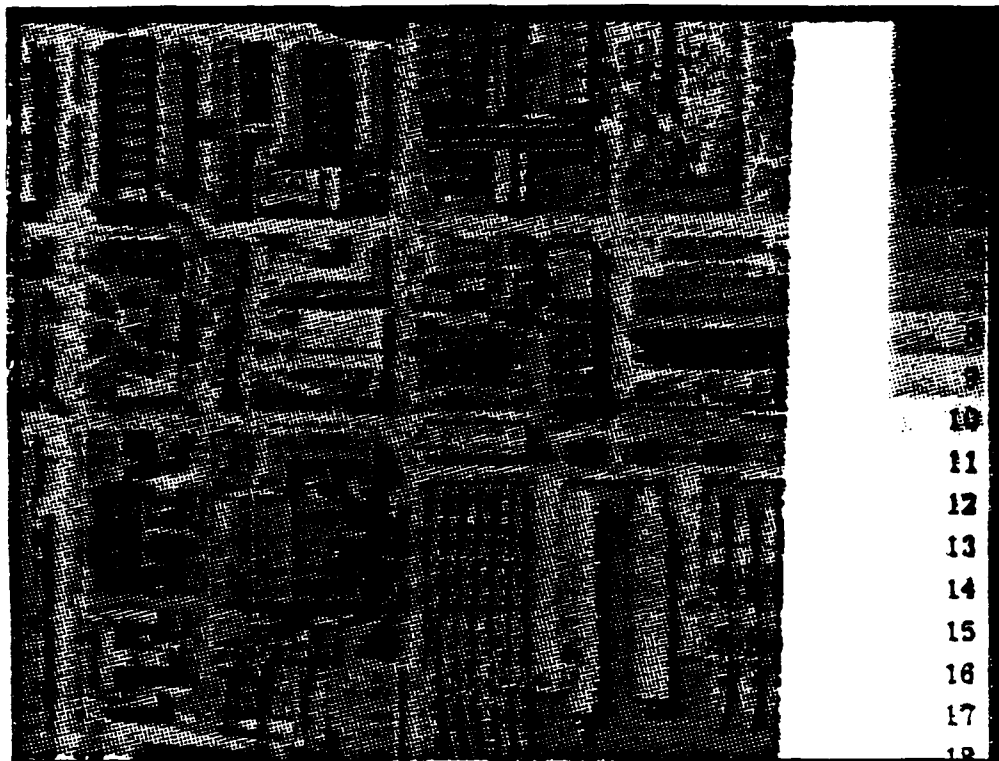


Figure 3.36 - Straight DPCM Encoded Aerial Photo

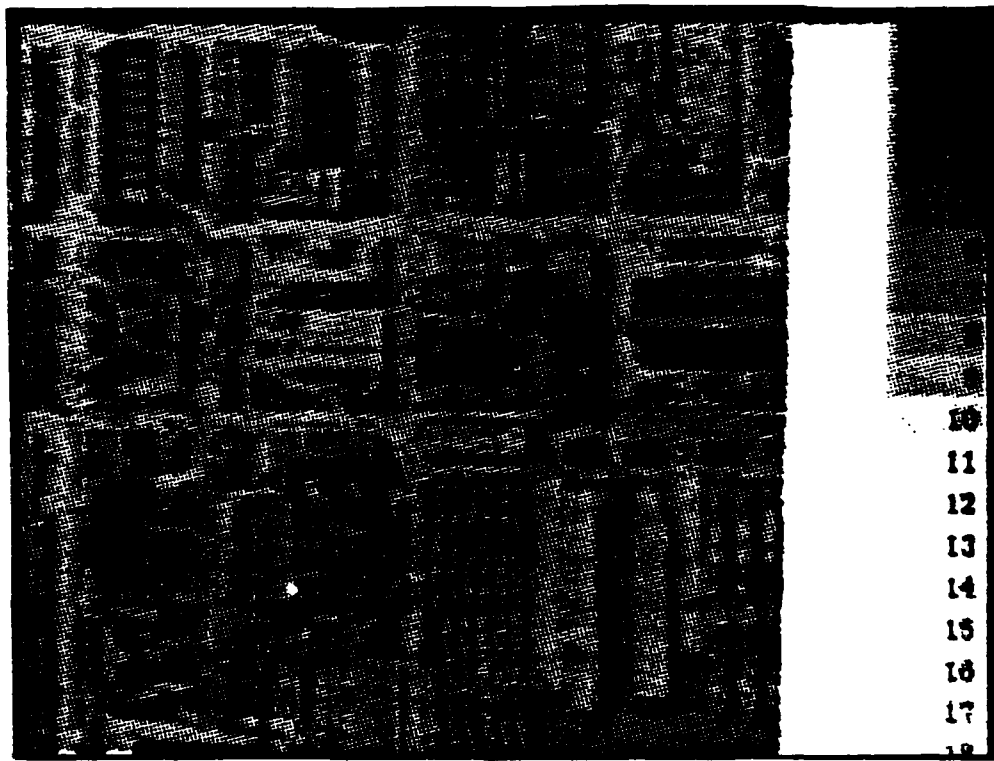


Figure 3.37 - Subsampled DPCM Encoded Aerial Photo

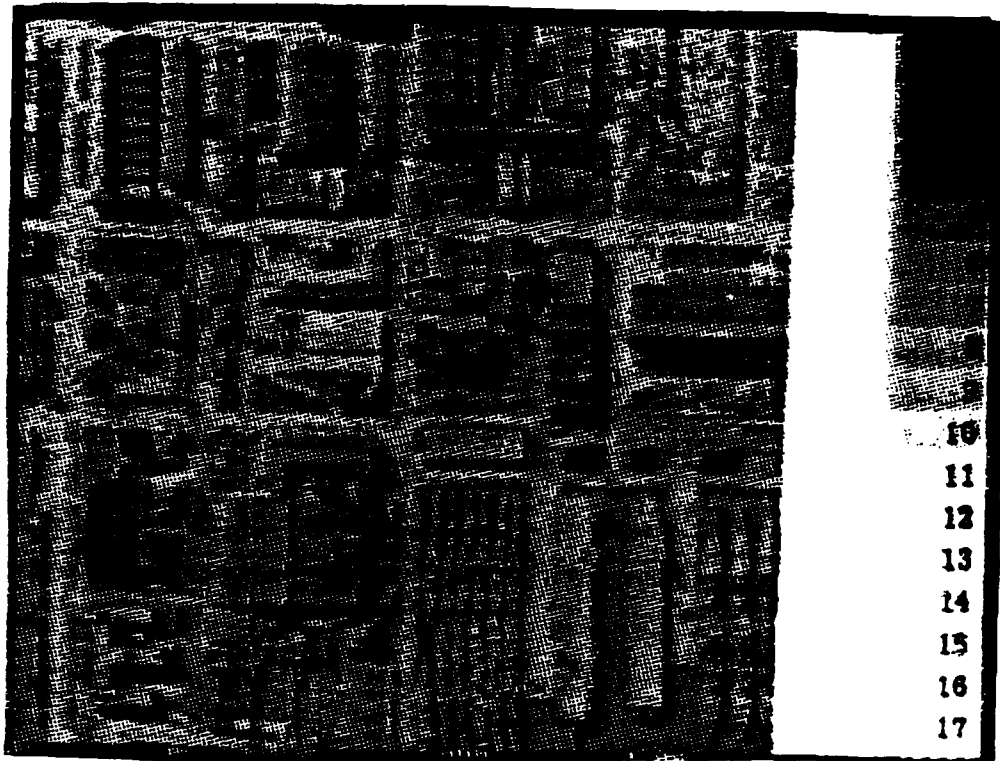


Figure 3.38 - Adaptive Zonal Encoded Aerial Photo

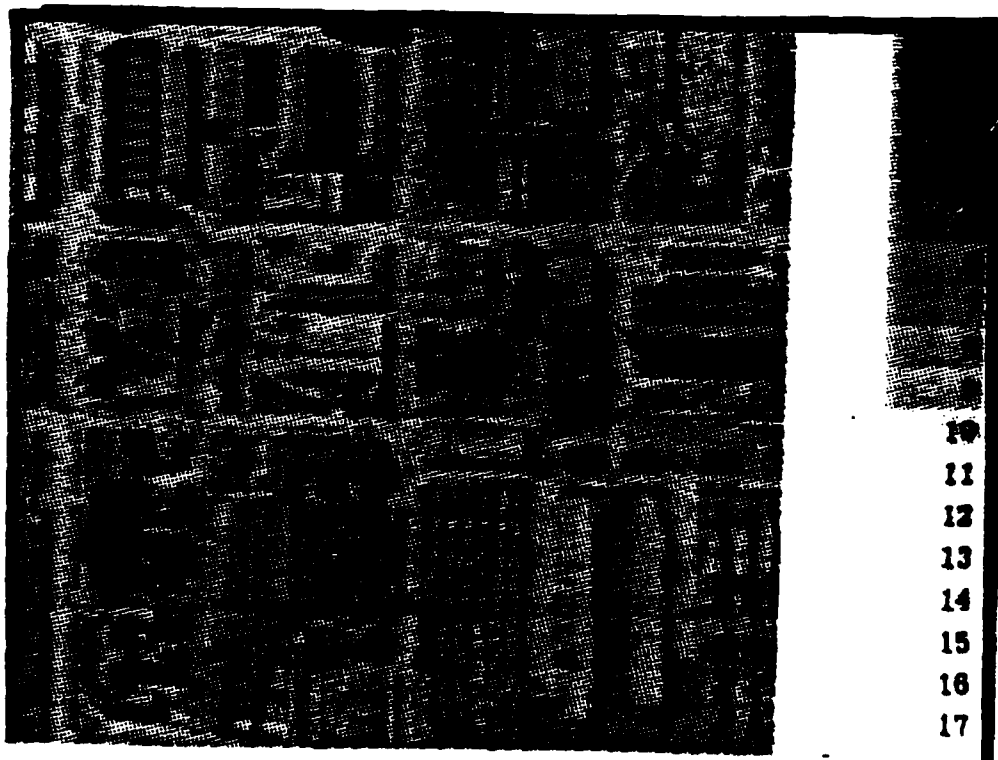


Figure 3.39 - Image Dependent Chen-Smith Encoded Aerial Photo

adaptive ordered dithering with bit reordering and adaptive ordered dithering with bit interleaving simulations are also represented by one image (referred to in Table 3.2 as "Pre-transmission, Ad. Ordered"), as the respective rearrangement steps have no effect on the image quality.

Of the dither compression techniques studied, the adaptive clumped dithering with clump plane separation algorithm appears to have produced the best combination of compression and output image quality. The adaptive ordered dithering with bit interleaving algorithm produced the most compression of the algorithms simulated, followed closely by the adaptive ordered dithering with bit reordering algorithm; the image quality produced by adaptive ordered dithering was slightly less impressive than that produced by adaptive clumped dithering.

As stated earlier, the transform coding simulations could have produced greater compression, but would not have produced images comparable in quality to those produced by the adaptive clumped dithering or adaptive ordered dithering algorithms. The image quality produced in the transform coding simulations was inferior to that produced in the pre-transmission algorithm simulations, even though lower compression was achieved. The DPCM coding simulations also did not perform as well as the pre-transmission techniques in terms of either compression or output image quality.

Before beginning the analysis of the output images, it should be noted that not all of the artifacts apparent in these

images are due to the compression and/or dithering algorithms. In several of the output images (most notably those in which the house and sky test image was employed), vertical and/or horizontal lines are evident. These lines are characteristics of the printing process employed and thus were not considered in evaluating the dithering techniques.

The effect of the adaptive vs. non-adaptive dithering techniques is most evident in the output images of the simulations in which the IEEE test chart image was employed. In comparing Figures 3.8 and 3.9 and Figures 3.10 and 3.11, respectively, it is evident that the non-adaptive dithering techniques produce a "graying" effect in two-tone regions of the image. The "graying" is most apparent in the blurring of the smaller characters associated with the resolution wedge and in the Moire patterns present in the radial test pattern. The adaptive dithering techniques apply a single threshold to the image regions containing two-tone information and thus eliminate the loss of edge sharpness in these areas.

In comparing clumped dithering to ordered dithering in terms of output image quality, the overall quality of the clumped dithered images in Figures 3.8, 3.16, 3.24, and 3.32 is better than that of the ordered dithered images in Figures 3.11, 3.19, 3.27, and 3.35. The clumped dithered images contain more contrast than the ordered dithered images, and more detail is evident (e.g. window features in Figure 3.16 vs. Figure 3.19). Ordered dithering processed vertical edges much better than

clumped dithering; in Figure 3.16, the vertical lines on the left side of the house are jagged, while in Figure 3.19 they are straight.

The clumped dithered images exhibit more contouring in the smooth regions of the images. Contouring is evident in the smooth regions of the face and background in Figure 3.8 but is not evident in the ordered dithered image in Figure 3.11. Contouring occurs in image areas where the gray level changes on a finer level than the pseudo-gray scale of the algorithm can represent. Because clumped dithering employs a 17-threshold dither matrix, as opposed the 32-threshold dither matrix employed in ordered dithering, the clumped dither matrix can not represent as many pseudo-gray levels.

The ordered dithering images exhibit less contrast than the clumped dithered images because the ordered dither thresholds are spread linearly across the dynamic gray scale range. The clumped dither thresholds produce more contrast because they are spread non-linearly; they were selected in order to closely simulate the photo-mechanical screening process.

The post-transmission dithering techniques produced output images of somewhat lower quality than those produced by the pre-transmission dithering techniques. In comparing Figures 3.8 and 3.12, the loss in image quality due to the 3-bit quantization process associated with DPCM coding can be detected in the bi-level image areas; many of the characters appear blurred. When subsampling was employed in the DPCM algorithm in order to

produce compression on the order of that produced by the pre-transmission dithering techniques, this blurring became more pronounced, and a loss of detail in the gray scale areas of the images became evident (compare images 3.24 and 3.29).

The two transform coding algorithms produced very good image quality for the images containing predominantly gray scale information. However, in the simulations in which the IEEE test chart image was employed, the transform coding algorithms did not perform as well as the pre-transmission dithering techniques. The adaptive zonal transform coding algorithm produced compression comparable to that produced by the pre-transmission dithering techniques, but the resulting output image (Figure 3.14) contains artifacts caused by the "blocking" effect characteristic of transform coding. The image dependent Chen-Smith transform coding algorithm produced image quality close to that produced by the adaptive clumped dithering pre-transmission technique, but performed poorly in terms of compression.

4.0 CONCLUSIONS AND RECOMMENDATIONS

In analyzing the results presented in Section 3.0, several conclusions were drawn concerning the performances of the dither coding algorithms simulated. These conclusions, in turn, led to the formulation of a number of recommendations as to which direction future research into gray scale compression studies involving dither coding should be directed.

4.1 Conclusions

1. The adaptive clumped dithering with clump plane separation algorithm produced the best overall results in terms of compression, complexity of implementation, and output image quality. If the clump plane separation step is made optional, a slight loss in compression allows a gray scale capable facsimile machine to send a dithered image to a non-gray scale capable machine.
2. The adaptive ordered dithering simulations produced better compression results than the adaptive clumped dithering simulations while achieving relatively good image quality. A non-linear ordered dither threshold distribution over the dynamic gray scale range could improve the image quality of the adaptive ordered dithering algorithms.

3. The pre-transmission dithering compression techniques outperformed the post-transmission techniques in terms of compression and output image quality. For those applications in which a multi-level gray scale image is required at the receiver, the image dependent Chen Smith transform coding algorithm would produce very good dithered image quality and would perform fairly well in terms of compression, but would add a great deal of complexity to the equipment. The adaptive zonal transform coding algorithm could would be less complex to implement and could produce compression comparable to that of the Chen-Smith algorithm, but would not produce comparable image quality.

4. DPCM coding would greatly reduce the complexity of a system requiring full gray scale images at the receiver, but would be limited in terms of achievable compression. The optional subsampler has little visual effect on the multilevel gray scale images, but produces significant distortion when the subsampled images are dithered.

4.2 Recommendations for Further Study

1. Investigate variations of the clump plane separation algorithm in order to improve the compression performance of the adaptive clump dithering with clump plane separation algorithm. It may be possible to improve the compression

performance of this algorithm to the point where it is equal to or better than that of the adaptive ordered dithering algorithms, thus eliminating the tradeoff between image quality and added compression.

2. Optimization of the ordered dither threshold distribution over the dynamic gray scale range should be performed in order to improve the image quality produced by this dithering algorithm. It may be possible to improve the output image quality of this algorithm to the point where it is equal to or better than that of the clumped dithering algorithm, thus eliminating the tradeoff between image quality and added compression.

3. Investigate the application requirements of gray scale image transmission over Group 4 facsimile more closely to determine whether multilevel gray scale imagery at the receiver is desirable. If so, determine the relative importance of image quality vs. compression vs. complexity to determine which of the post-transmission dithering techniques should be analyzed more closely.

References

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3. Delta Information Systems, "Computer Simulation of Gray Scale Coding Techniques," Contract number DCA100-83-C-0072, Task Order no. 2, December 1984.
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