Comparison of Redundancy Reducing Codes for Facsimile Transmission of Documents

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(Invited Paper)

Abstract—A comparison and a valuation of different redundancy reducing coding techniques for the digital transmission of facsimile documents on telephone lines is presented. Especially taken into account are those codes which have been submitted to the International Telegraph and Telephone Consultative Committee (CCITT) for standardization of digital group 3 facsimile machines. The reduction factor and the sensitivity of channel errors of these one- and two- dimensional codes have been investigated by computer simulations using the CCITT test documents and burst error patterns of real telephone lines. For a resolution of 1728 picture elements per line and 3.85 lines per mm one-dimensional run length coding proves to be the most economical solution. Using a higher vertical resolution of 7.7 lines per mm the effects of transmission errors are less visible in the received document and two-dimensional codes become more efficient. To achieve a transmission time of 1 min or less for a size $A4$ document a transmission bit rate of 4800 bits/s is required. For the higher vertical resolution a transmission time of 1 min cannot be guaranteed for all types of documents with this bit rate even if two-dimensional coding is used.

1. INTRODUCTION

IN THE CCITT Study Group XIV different source encoding techniques for the digital transmission of facsimile pictures with only black and white picture elements ("pels"), like drawings, business letters or printed matter, are currently being discussed for standardization. The aim is to transmit a size $A4$ page (8.27″ × 11.69″) within one min or less over the public switched telephone network. This requires a redundancy reducing encoding scheme to compress the amount of binary data to be transmitted.

The sequence of picture elements of a line-scanned facsimile picture consists of strings of white pels separated by strings of black pels. These strings are called white and black "runs". Normally the black runs are shorter than the white runs and there is a strong correlation between the positions of black runs in subsequent scan lines. It is this structure in the arrangement of black and white pels which determines the amount of redundancy in the picture and hence the possible compression gain. A theoretical treatment of the concepts of facsimile source encoding is given in a paper by T. S. Huang in this issue. Many coding techniques have been designed which describe the picture by coding in some way the position and the length of white and black runs. They form the important class of run length coding schemes. Some of them are one-dimensional run length codes which make use only of the statistical dependency of adjacent picture elements within the scan line [1-3]. Other more complex schemes also exploit the line-to-line dependencies of a picture [4-8] and are denoted here as two-dimensional coding schemes.

In order to get comparative results for different coding proposals some selected codes were simulated on a computer and were applied to a set of 8 test documents selected by the CCITT. The number of code bits was counted and the reduction factor was determined as the total number of picture elements divided by the number of code bits. For investigating the transmission error sensitivity of the codes data transmission experiments were carried out with the aim of storing typical bit error patterns which occur on telephone lines in a computer. In this manner exactly the same realistic error patterns could be applied to different codes, documents and resolutions using selected 1 to 2 min long segments from the stored "frozen" channel characteristic. Using the disturbed code words the pictures were reconstructed and printed out in order to evaluate subjectively the influence of the transmission errors on the picture quality.

In chapter 2 the coding schemes are outlined which have been selected for this comparison. The measured reduction factors of these codes are presented in chapter 3. In chapter 4 the influence of the transmission errors on the decoded pictures is discussed. The results of the overall valuation are summarized in the conclusion.

2. SELECTED CODING SCHEMES

The following one- and two-dimensional coding schemes were selected for the comparison.

One-dimensional coding schemes

B_1-code [1]
Truncated Huffman code [2]
Modified Huffman code [3]

Two-dimensional coding schemes

Kalle-Infotec code (Dacom) [4], [5]
Kokusai Denshin Denwa code [6]
TUH-code [7], [8]

The one-dimensional run length coding schemes transmit the length of white and black runs within a scan line. They differ from each other mainly by modifications of the assignment of code words to the run lengths. As an example Fig. 1 shows such an assignment for the B_1-code [1]. Each code word consists of one or more 2-bit-segments. The first bit C in each segment indicates the color of the coded run, e.g. white = 0 and black = 1. Subsequent 2-bit-segments with the same color bit form a code word. The remaining bits assume all the possible binary combinations. Neglecting the color bit only two different 2 bit-code words are possible. Then another segment is added and four more code words can be formed. Thus

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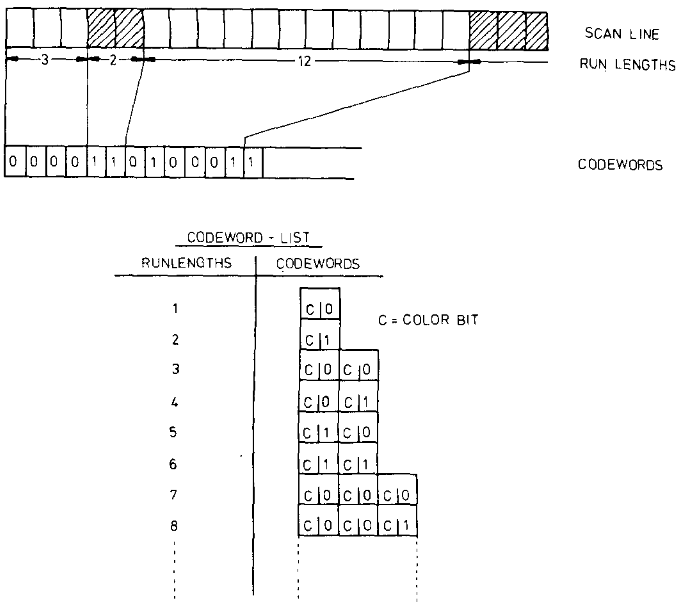


Fig. 1. Coding example for the B_1-code. C indicates the color of a run.

short code words are assigned to the more frequent short runs and longer code words are assigned to the seldom occuring long runs. The same code word assignment is used for white and black runs.

The problem of assigning code words to the run lengths in an optimal way can be solved by using the algorithm of Huffman [9], which minimizes the average code word length for a given probability distribution of the run lengths. Since the probability distribution is different for white and black runs individual code word sets must be provided for coding the white and black runs respectively. However, since the code words are assigned according to the probabilities of the run lengths there is no simple rule for calculating directly the code word from the run length and vice versa. Therefore these Huffman coders and decoders must have available stored code word tables both for the white and the black runs up to the maximum run length of 1728 pels, for example. This implies a high implementation complexity which can be reduced considerably without losing much of the compression gain by providing individual Huffman code words only for the frequently occurring short runs and coding longer runs in a different way. Two proposals of this type have been made to the CCITT, the Truncated Huffman code [2] and the Modified Huffman code [3].

The Truncated Huffman code assigns Huffman code words to white run lengths up to 47 pels and to black run lengths up to 15 pels with a different code word table for white and black runs (Table 1). White runs longer than 47 pels are coded with a 3 bit prefix word followed by an 11 bit word which represents the run length as a binary number. In the same manner black runs longer than 15 pels are coded with a 7 bit prefix plus an 11 bit binary number. At the beginning of each scan line a 17 bit synchronizing word is transmitted in order to limit the effects of transmission errors to one scan line. For totally white scan lines only the synchronizing word is sent.

The Modified Huffman code assigns individual Huffman "terminating" code words to run lengths up to 63 pels (Table 2). A different list of code words is provided for white and black run lengths. Run lengths in the range of 64 to 1728 pels are encoded by two Huffman code words, by a "make up" code word which represents a multiple of 64 pels and by a corresponding "terminating" code word which indicates the difference between the required run length and that multiple of 64 pels. The code also provides a scan line synchronizing word consisting of 10 zeros followed by a one. For totally white scan lines the "make up" and "terminating" code representing a white run of 1728 pels is sent.

TABLE 1
CODE WORD ASSIGNMENT FOR THE TRUNCATED HUFFMAN CODE

run length	code words for white runs	code words for black runs
1	111111	01100
2	01101	10
3	10001	00
4	1001	010
.	.	.
.	.	.
.	.	.
15	110110	11010011
.	.	
.	.	
.	.	
47	1111100010	
>47	010 + 11 bit - run length	
>15		1101000 + 11 bit - run length
line synchronizing word	00000000000000001	

TABLE 2
CODE WORD ASSIGNMENT FOR THE MODIFIED HUFFMAN CODE

run length	code words for white runs	code words for black runs
0	00110101	0000110111
1	000111	010
2	0111	11
3	1000	10
4	1011	011
.	.	.
.	.	.
.	.	.
63	00110100	000001100111
64	11011	0000001111
128	10010	000011001000
192	010111	000011001001
.	.	.
.	.	.
.	.	.
1728	010011011	0000001100101
line synchronizing word	00000000001	

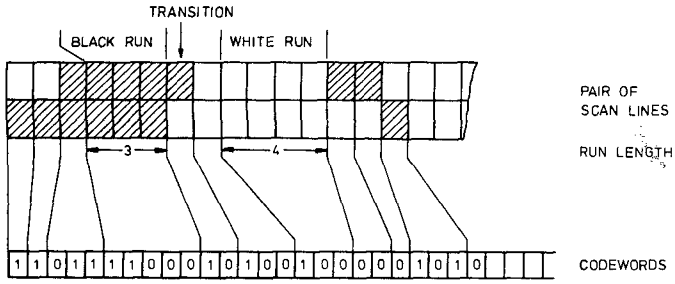


Fig. 2. Coding example for the Kalle-Infotec-code.

The Kalle-Infotec code [4], [5] works on a pair of subsequent scan lines which are segmented into white and black runs and transitional regions (Fig. 2). The double line runs are transmitted with an adaptive run length code which changes its basic word length between 2 bits and 8 bits according to the local statistics of the facsimile picture. The current word length can be different for white and black runs. The type and the length of the transitional regions are characterized by special prefix and identification bits.

The coding scheme proposed by Kokusai Denshin Denwa (KDD) [6] uses the line to line correlation in a different way (Fig. 3). A color change at position Q in the current scan line is indicated by transmitting the horizontal distance to one of two reference points, P or Q'. Q' is the position of the corresponding color change in the previous scan line and P is the position of the last color change in the current scan line. The shorter one of the two distances PQ and QQ' is coded and transmitted. For very frequently occuring events like $QQ' = 0, +1, -1$ as well as for the distinction between the cases PQ and QQ' special Huffman code words are provided. The run lengths for PQ and $|QQ'| > 1$ are coded by a run length code which is rather similar to a B-type code with 3-bit-segments.

The TUH-code [7], [8] works on the picture elements of a scan line in two consecutive steps. First a two-dimensional prediction of the current picture element X_0 is made using the neighboring pels X_1 to X_4 from the same and from the previous scan line (Fig. 4a). Each black-and-white pattern of these four pels defines a different source state S_j. For each state there are individual conditional probabilities $P(X_0/S_j)$ that the present picture element X_0 will be white or black. Now the prediction value for X_0 is determined as the brightness level which is the more probable one in the given source state S_j. Then the prediction value is compared to the real value of X_0. Each time the prediction is right, a white pel is inserted for X_0. When the prediction is wrong, X_0 is replaced by a black pel. The resulting picture of prediction errors is a one-to-one transformation of the original picture, which means that all the information of the original picture can be represented by coding in some way the positions of the prediction errors.

The second step in the coding algorithm is to encode the run lengths between prediction errors, as shown in Fig. 4b. The runs which are assumed to be statistically independent are coded here separately for each state S_j of the source. For example, the source is five times in state S_0 until the first prediction error occurs in state S_0. So the run length to be transmitted is 5. For state S_1 there is a prediction error when the state S_1 occurs the third time, so the run length is 3, etc. In a practical encoder the separate transmission of

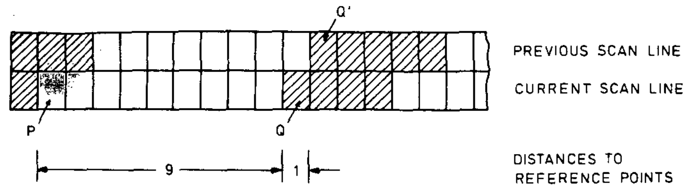


Fig. 3. Coding principle of the KDD-code.

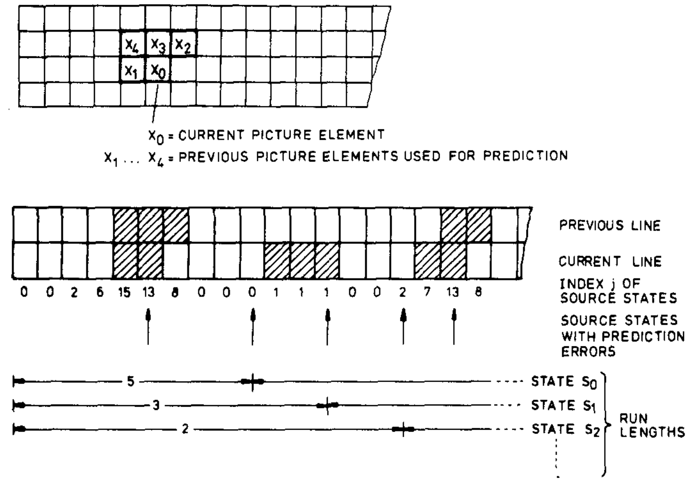


Fig. 4. Coding principle of the TUH-code.

the run lengths for the different source states can be done on a line by line basis. The run lengths are coded by means of Truncated Huffman codes which were individually optimized for each source state S_j using the statistics of typewritten text.

3. COMPARISON OF THE REDUCTION FACTORS

The described codes were simulated on a computer and were applied to a set of 8 test documents selected by the CCITT (Fig. 5). The test documents were digitized with 1 bit/pel for the resolutions

a) 1728 pels/line (8 pels/mm), 3.85 lines/mm and
b) 1728 pels/line (8 pels/mm), 7.7 lines/mm

and stored on computer magnetic tape. The above resolutions are recommended by the CCITT for the transmission of documents with digital facsimile machines. The reduction factors were measured for the different codes and resolutions as the total number of picture elements divided by the number of code bits necessary to transmit the picture. This number includes all additional bits like parity bits or line synchronizing words as proposed for the coding schemes in order to limit the effects of transmission errors to a small area on the picture. In the case of the KDD-code and the TUH-code it was assumed that the coder transmits every fourth scan line only one-dimensionally ($k = 4$) in order to stop the vertical propagation of transmission errors. The number of code bits to be transmitted does not include, however, stuffing bits which have to be inserted sometimes due to a possibly too slow line feed mechanism.

Table 3 contains the reduction factors for the 8 test documents and for the resolutions specified before. In order to

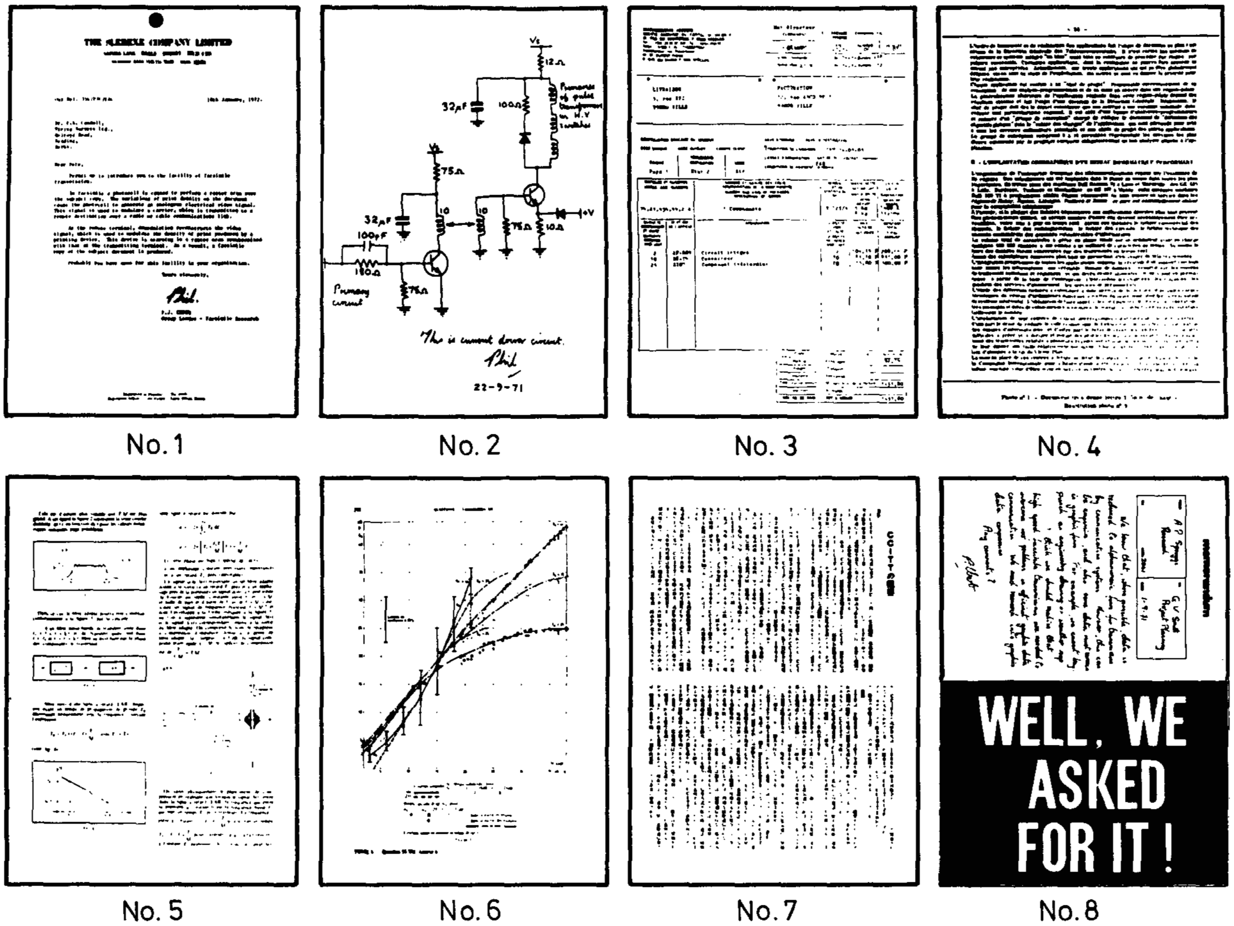


Fig. 5. CCITT-test documents. Original size of each document: ISO A4 (8.27" × 11.69").

TABLE 3
REDUCTION FACTORS

Resolution	Document	B_1- Code	Truncated Huffman Code	Modified Huffman Code	Kalle-Infotec Code	KDD-Code (k=4)	TUH-Code (k=4)
1728 pels/line 3.85 lines/mm	1	13.62	17.28	16.53	14.24	16.67	2o.32
	2	14.45	15.o5	16.34	18.99	24.66	24.94
	3	8.oo	8.88	9.42	8.89	1o.42	11.57
	4	4.81	5.74	5.76	4.66	4.52	5.94
	5	7.67	8.63	9.15	8.43	9.39	11.45
	6	9.78	1o.14	1o.98	12.57	15.41	17.26
	7	4.6o	4.69	5.2o	4.54	4.56	5.28
	8	8.54	7.28	8.7o	1o.99	12.85	13.1o
1728 pels/line 7.7 lines/mm	1	13.62	17.28	16.53	15.75	19.68	24.66
	2	14.45	15.o5	16.34	2o.93	28.67	28.99
	3	8.oo	8.88	9.42	1o.o3	12.o6	14.96
	4	4.81	5.74	5.76	5.27	5.42	7.52
	5	7.67	8.63	9.15	9.44	1o.97	13.82
	6	9.78	1o.14	1o.98	13.86	17.59	19.96
	7	4.6o	4.69	5.2o	5.oo	5.36	6.62
	8	8.54	7.28	8.7o	12.o1	14.73	15.o3

give a better insight the transmission times with a transmission bit rate of 4800 bits/s were calculated from the reduction factors. They are shown in Figs. 6-8. The reduction factors of the one-dimensional codes are independent of the vertical resolution, i.e. doubling the scan line density will also double the transmission time. The reduction factors of the two-dimensional codes show an average increase by 16% with doubling of the vertical resolution. This corresponds to an increase by 72% of the transmission time compared to that of the lower resolution.

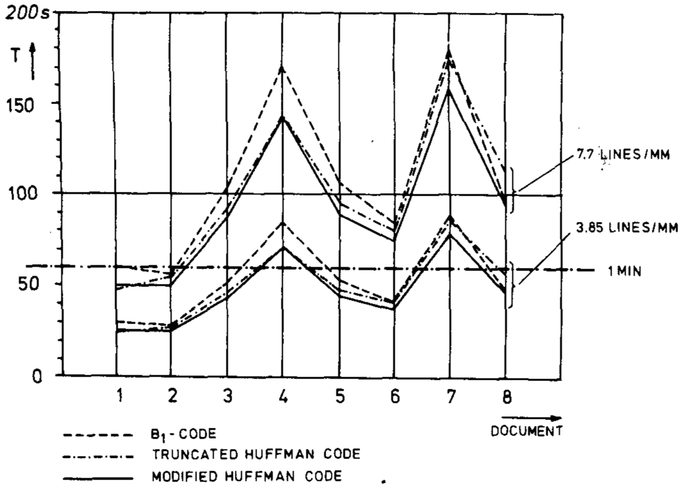


Fig. 6. Transmission times for the one-dimensional codes. Resolution: 1728 pels/line, 3.85 and 7.7 lines/mm. Transmission bit rate: 4800 bits/s.

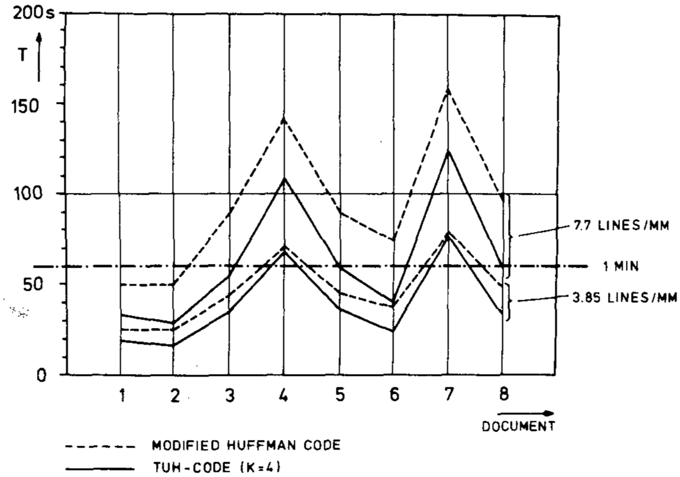


Fig. 8. Transmission times for a one-dimensional and a two-dimensional code. Resolution: 1728 pels/line, 3.85 and 7.7 lines/mm. Transmission bit rate: 4800 bits/s.

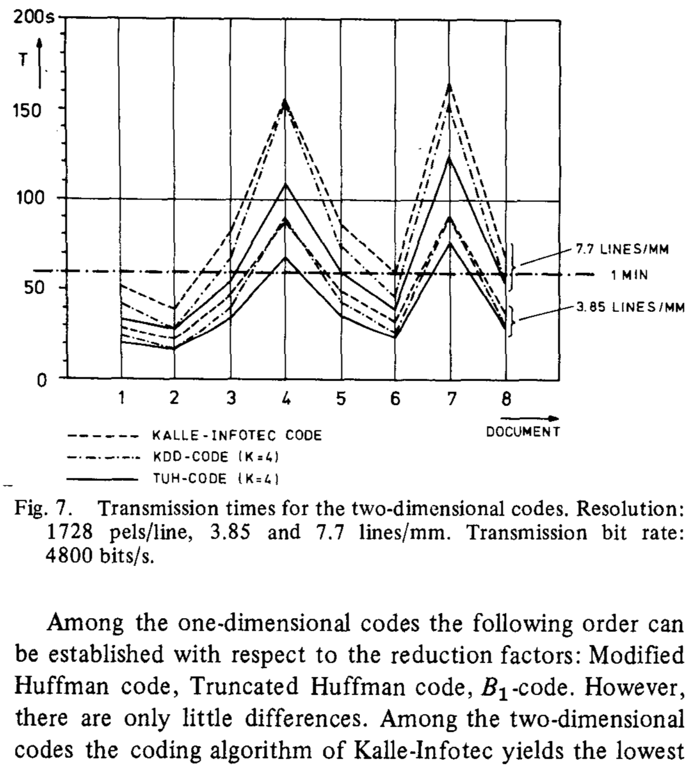


Fig. 7. Transmission times for the two-dimensional codes. Resolution: 1728 pels/line, 3.85 and 7.7 lines/mm. Transmission bit rate: 4800 bits/s.

Among the one-dimensional codes the following order can be established with respect to the reduction factors: Modified Huffman code, Truncated Huffman code, B_1-code. However, there are only little differences. Among the two-dimensional codes the coding algorithm of Kalle-Infotec yields the lowest reduction factors in most cases. For text information, e.g. test documents 1, 4 and 7, the reduction factor is even lower than with some of the one-dimensional codes. Generally the increase of the reduction factor with two-dimensional coding compared to one-dimensional coding is much less for text information than for drawings. The most effective two-dimensional coding algorithm is the TUH-code, especially for text information.

Fig. 8 shows a comparison of the transmission times both for the most effective one-dimensional and two-dimensional code, using a transmission bit rate of 4800 bits/s. The shortest transmission times are obtained for those documents which contain only a few text lines or contours, as for example a business letter (document 1) or drawings (documents 2 and 6). Full text pages require considerably longer transmission times which can be in the range of 2 to 3 min for the high vertical resolution (documents 4 and 7). It is evident from Fig. 8 that the two-dimensional coding scheme yields a substantial additional gain compared to the one-dimensional algorithm only for the high vertical resolution of 7.7 lines/mm. The difference of the transmission times is much less for the low vertical resolution, especially for documents which contain text information.

4. INFLUENCE OF TRANSMISSION BIT ERRORS

In a one-dimensional coding algorithm a channel error will change a code word so that the corresponding run length will be recorded too long or too short at the receiver after decoding. In case of a Huffman type code even more information is lost because the decoder needs a certain interval to fall back into the correct code word segmentation. This will cause a spatial shift of the subsequent picture information which, however, can be limited to one scan line by introducing a synchronizing word at the beginning of every scan line. Additionally the receiver can sum up the decoded run lengths between two synchronizing words and detect the occurrence of channel errors by comparison of the result with the nominal scan line length. In case of an error the receiver can omit the disturbed scan line and can record the previous scan line instead. Thus, the line-to-line correlation is used for the error correction.

Such a system cannot be employed with two-dimensional coding algorithms. In the Kalle-Infotec coding scheme a channel error will always affect two adjacent scan lines. In order to limit the influence of transmission errors on the reconstructed picture the sequence of code bits is segmented into blocks of 512 bits which are then supplemented by a cyclic redundancy check code for error detection and special synchronizing information. In case of an error the false block is suppressed at the receiver and the corresponding double line segment is recorded as a white streak.

In the case of the KDD- and TUH-code channel errors can destroy up to 4 adjacent scan lines which are simply suppressed at the receiver after detection of an error. For the detection of errors the code words are supplemented by framing words and parity bits. The resulting picture quality can be improved, if the one-dimensional coding mode is used every second scan line ($k = 2$), but then the reduction factor decreases.

For the investigations reported here the structure of bit

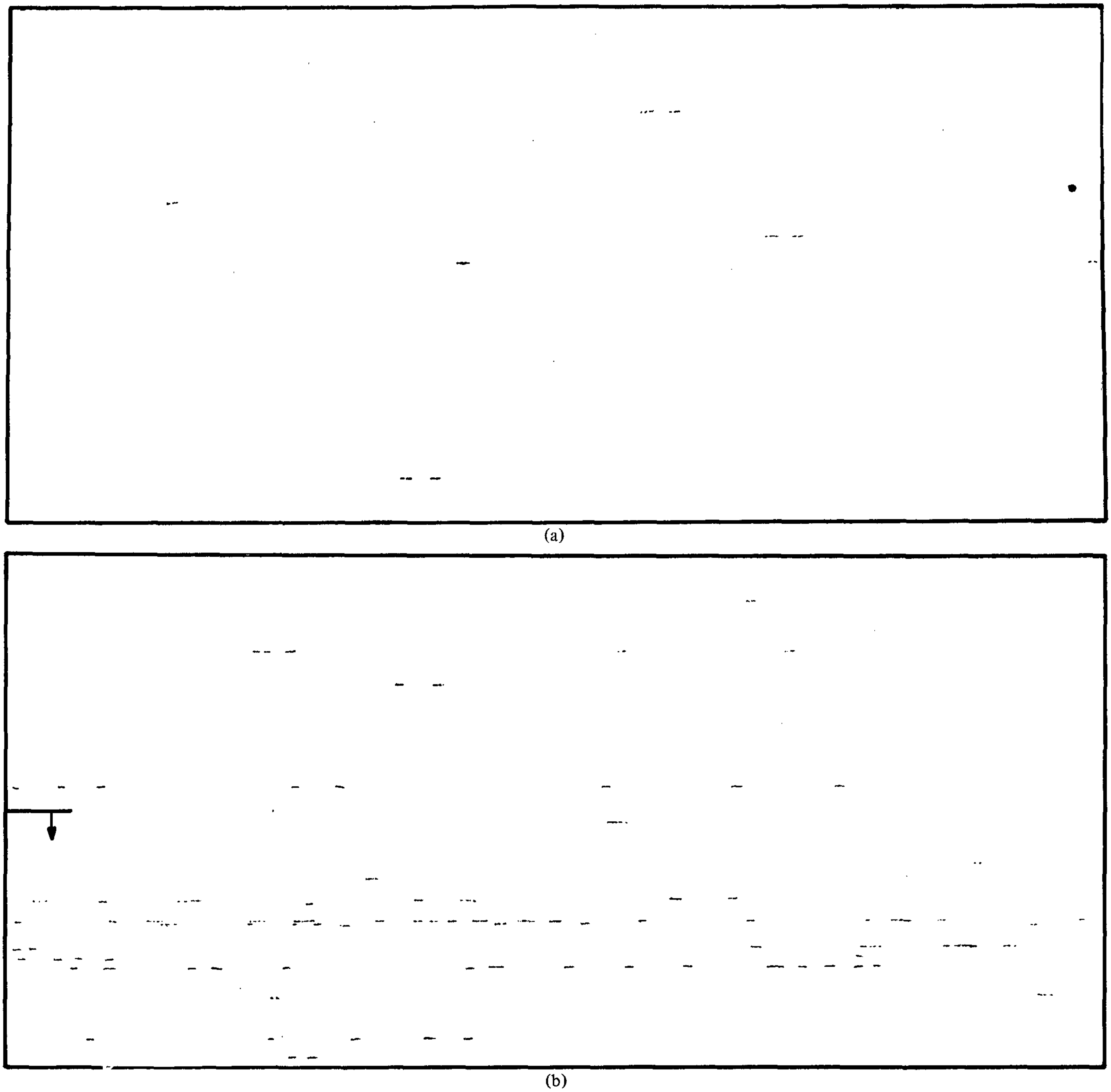
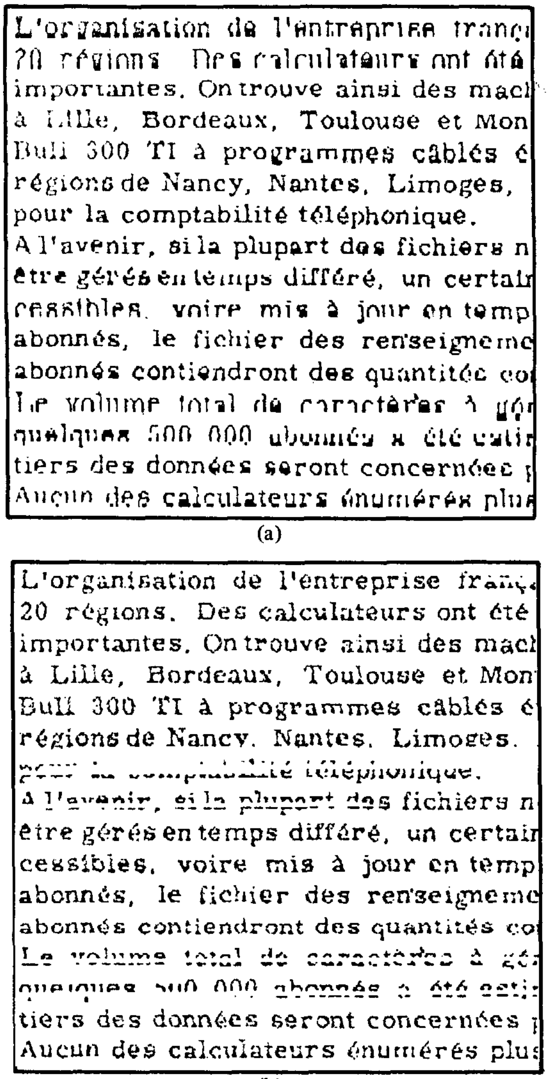


Fig. 9. Examples for bit error patterns on telephone lines with 4800 bits/s transmission bit rate. The resolution of the shown patterns is 1728 pels per line and 7.7 lines per mm. Thus each pattern corresponds to about 4 min transmission time. Transmission bit errors are represented by black picture elements. (a) Directly dialed line between Darmstadt and Hannover; average bit error rate of the 15 min transmission experiment: 5.8×10^{-5}. (b) Line with 6 FDM-segments; average bit error rate of the 15 min transmission experiment: 6.1×10^{-4}.

errors on telephone channels was measured by transmitting a 511 bit pseudorandom bit sequence according to the CCITT recommendation V.52 over the public switched telephone network in Germany from the "Fernmeldetechnisches Zentralamt (FTZ)" of the German PTT in Darmstadt to the Technical University in Hannover (TUH). The telephone links were built up by dialing from Frankfurt to Darmstadt and from Hamburg to Hannover, whereas between Frankfurt and Hamburg a variable number of FDM-segments (frequency division multiplex) were introduced. A sequence of 25 transmission experiments each of about 15 min duration, was performed both with 2400 and with 4800 bits/s transmission rate. The received data were stored in Hannover on digital magnetic tape and processed in a computer in order to extract the bit error structure and make it available for further processing with coded pictures. In this manner exactly the same error pattern could be applied to different codes and facsimile documents with different resolutions using special 1 to 2 min long segments from the stored bit error sequences.

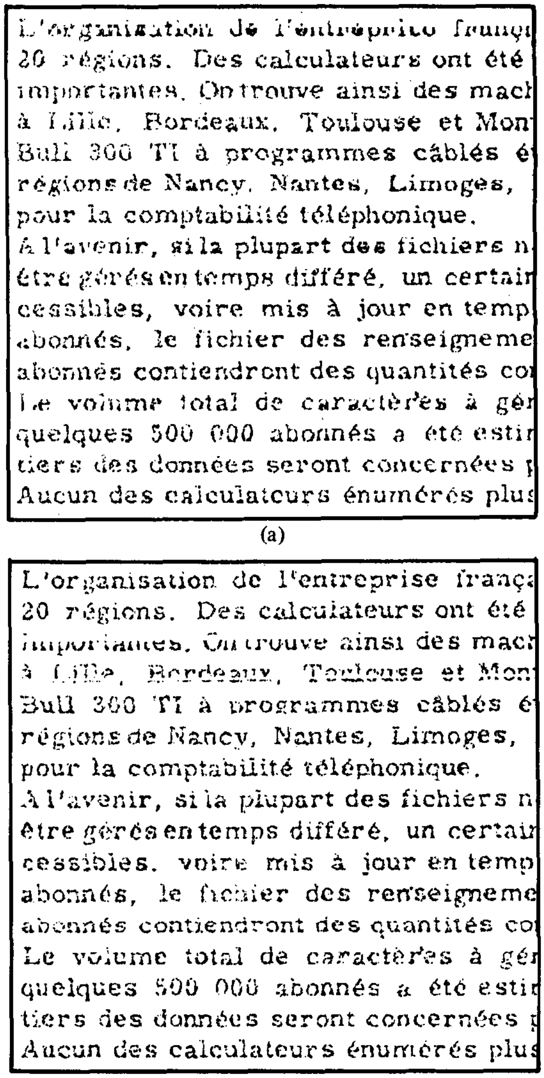
Fig. 9 shows two examples of 4 min long segments of bit



(a)

(b)

Fig. 10. Worst case error pattern of Fig. 9b applied to the Truncated Huffman code.



(a)

(b)

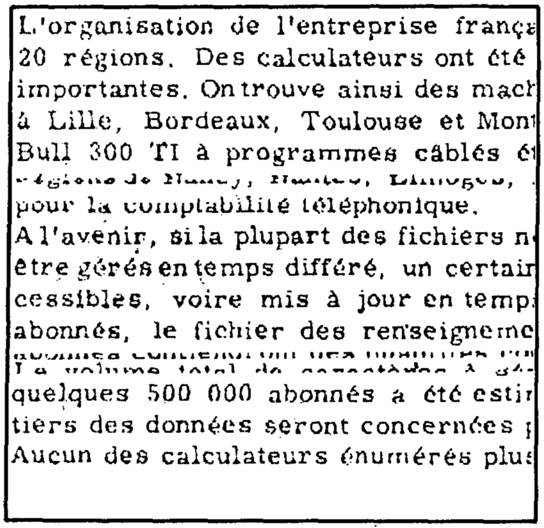
Fig. 11. Worst case error pattern of Fig. 9b applied to the Kalle-Infotec code.

error patterns encountered during the experiments. These pictures were obtained by applying the stored error sequences to the PCM representation of a white page with 1 bit/pel using the resolution of 1728 pels/line and 7.7 lines/mm. Thus each bit error is marked by a black pel on the page. The first example of Fig. 9a represents a rather normal case with only few errors, whereas Fig. 9b shows a worst case example with an extreme amount of burst errors. The bit error rates given in Fig. 9 refer to a transmission experiment of 15 min duration. The bit error rates measured for 25 transmission experiments were in the range of $2.1 \cdot 10^{-5}$ to $1.2 \cdot 10^{-3}$ depending on the number of FDM-segments introduced. Generally the 4800 bit/s modem performed somewhat better than the 2400 bit/s modem due to the influence of the adaptive equalizer in that modem.

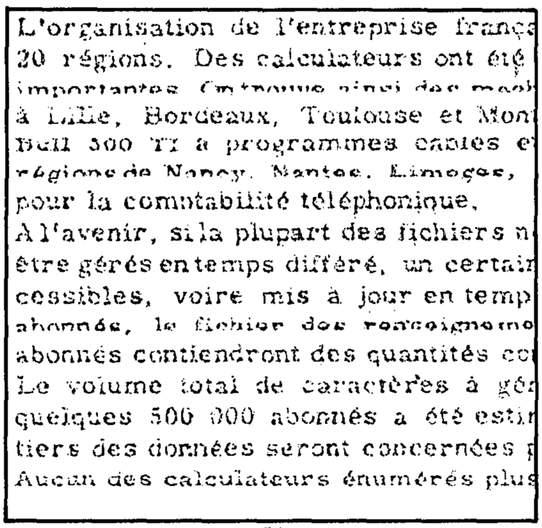
The stored error patterns were applied to the Truncated Huffman code, the Kalle-Infotec code and the KDD-code by means of computer simulations. The Truncated Huffman code is representative of the class of one-dimensional Huffman type coding schemes and the KDD-code also represents the error performance of the TUH-code. Figures 10 through 12 show as a worst case example test document 4 processed with a part of the error pattern in Fig. 9b beginning at the marked position. This pattern of extreme error bursts was chosen in order to have many errors on a page and also to demonstrate the resulting picture quality for the case where two or more adjacent scan lines are affected by channel errors. Since the error pattern is applied to the code bits the erroneous lines appear at different places on the picture for different codes and resolutions.

In the case of the one-dimensional Truncated Huffman code with substitution of erroneous lines by the previous line, single repeated scan lines are detectable but not annoying for the low vertical resolution. However, the picture quality becomes intolerable if two or more adjacent scan lines are destroyed by severe error bursts and have to be repeated (Fig. 10). With the high vertical resolution of 7.7 lines/mm single repeated scan lines cannot be detected and the picture quality is much better.

In the Kalle-Infotec coding algorithm erroneous double line segments are recorded as white streaks which are annoying with the low vertical resolution (Fig. 11). With the high resolution the white streaks are still visible but the picture quality is improved considerably. The Kalle-Infotec code could also benefit from line replacement to correct for blocks containing errors by using the appropriate portion of the previous scan



(a)



(b)

Fig. 12. Worst case error pattern of Fig. 9b applied to the KDD-code ($k = 4$).

line to replace the blank segment of the decoded upper line and the portion of the succeeding line to replace the blank segment of the decoded bottom line.

The suppression of up to 4 scan lines in case of an error in the KDD-coding scheme cannot be tolerated both with the low and with the high resolution (Fig.12). Such a coding scheme can be used only when the parameter k is reduced to $k = 2$ or when a data transmission system with bit error correcting facilities is available.

It should be pointed out that Figs. 10-12 represent a worst case example and that in normal cases the transmission errors are tolerable or not visible also for the resolution of 3.85 lines/mm. However, in these normal transmissions with only very few error bursts it also might happen that an error sequence disturbs two or more adjacent scan lines, which leads to impairments of the legibility of text information even for one-dimensional coding. Therefore it might be desirable not to leave out a whole scan line in case of an error but to preserve as much correct information of the disturbed line as possible. This could be done by locating the erroneous part of the line, e.g. by continuously checking the correlation to the adjacent lines, and repeating only that part of the line. Such an improved error correcting procedure has recently been proposed to the CCITT [10]. Investigations on this subject are just being performed, but the results are not yet available.

The variable block length format normally used for the single line algorithms is more vulnerable to loss of block or framing synchronization than the fixed block format, particularly if an error occurs in the synchronization code. Under these conditions two consecutive scan lines can be affected from a single bit error. A fixed block format similar to that used in the Kalle-Infotec code could also improve the error correction capabilities of the one-dimensional codes, especially if fly-wheeling techniques are used to compensate for bit errors in the synchronization code.

5. CONCLUSIONS

For the digital transmission of facsimile documents on telephone lines one- and two-dimensional source encoding algorithms have been proposed. A comparison shows that with the lower vertical resolution of 3.85 lines/mm and a transmission bit rate of 4800 bits/s an average transmission time of less than 1 min can be achieved for size $A4$ documents with all codes considered here.

For a resolution of 3.85 lines/mm there is no great difference between the transmission times of a one-dimensional and a two-dimensional code. Since one-dimensional codes are additionally less complex, less sensitive to channel errors and yield a better quality of the decoded and reconstructed picture these codes are more economical than two-dimensional codes. Therefore the CCITT study group XIV is presently working on the standardization of a one-dimensional coding algorithm for this resolution. Among the discussed coding schemes of this type, the Modified Huffman code is supported by a large group of study group members.

In the case of the higher resolution of 7.7 lines/mm the two-dimensional codes provide a considerably shorter transmission time than the one-dimensional codes. The average transmission time increases by 100% for one-dimensional and by about 70% for two-dimensional codes compared to those of the lower resolution. The subjective effects of transmission errors are reduced and the picture quality of some two-dimensional codes proves to be equal to that of the one-dimensional codes. Therefore two-dimensional codes appear more advantageous for the higher resolution, especially if the two-dimensional code is an extension of the one-dimensional code to be standardized.

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Digital Video: A Buffer-Controlled Dither Processor for Animated Images

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Abstract—A new technique has been discovered which permits pseudo-gray tone video images to be played in real-time on bilevel, memory displays such as the ac plasma panel. The technique combines ordered dither processing, selective updating, and hysteretic thresholding to digitally transmit or store the video images. Only a 1 bit/pel frame memory plus a 0.3 bits/pel replenishment buffer are required. This technique makes possible the use of a single terminal to display both graphic-alphanumeric information as well as pseudo-gray tone video images.

I. INTRODUCTION

We report on the development of a new technique enabling the design of an all digital visual communication system that employs a bilevel, flat, matrix-addressed display with long access times. Specifically, we use a commercially available ac plasma panel with memory[1] to display pseudo-gray tone video images representative of video telephone transactions. In addition we take broadcast TV material and display it at reduced quality on a CRT emulating bilevel displays of variable addressing speeds. This is made possible by simulating a gray scale with the ordered dither technique,[2,3] introducing a new form of conditional replenishment,[4,5] which we call selective updating, and modulating the dither thresholds with a buffer-controlled hysteresis. Our system is highly versatile, being capable of handling graphic-alphanumeric information as well as presenting animated images.

In the field of display technology there has been growing interest and some success in developing flat panel, matrix-addressed displays that would evolve as inexpensive replacements for CRTs and, perhaps more importantly, find applications that are presently beyond the capabilities of CRTs. Among the many candidate display technologies, such as gas discharge, electroluminescence, liquid crystals, and LEDs,[6] only the ac plasma panel[7] is both available commercially and has a resolution comparable to that of broadcast TV. However, the ac plasma panel was designed as a bilevel, memory display for a computer terminal and lacks an internal gray scale. Recently,[2,3] it has been shown that a reasonably good gray

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