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APPLICATION OF UNEQUAL ERROR PROTECTION CODES
ON COMBINED SOURCE-CHANNEL CODING OF IMAGES

K. FAZEL - J.J. LHUILLIER

LABORATOIRES D'ELECTRONIQUE PHILIPS
3, avenue Descartes, 94450 Limeil-Brévannes, France

ABSTRACT

This paper investigates a combined source-channel encoding of images with a small amount of redundancy. The source encoder under study is based on the Discrete-Cosine-Transform (DCT), adaptive quantization and variable length encoding (VLC) ; while the channel encoder is based on the unequal error protection (UEP) principle. To measure the importance of each bit in the transmitted frame after the VLC, a factor of sensitivity for each bit to channel errors is defined. By utilizing the factor of sensitivity, the optimal error rate allowed for each bit in the frame, that minimizes the effects of channel noise, is estimated. The performance of two UEP codes constructed by the Blokh-Zyablov code construction method, are evaluated for two sequences of images.

INTRODUCTION

To reduce the redundancy of digital TV images, different coding algorithms have been studied. The performance of such an algorithm depends mainly on its compression factor and the signal to noise power ratio (SNR) at the decoder side. The higher the compression factor at the source, the greater is the significance of the transmitted information, and hence the greater the effects of channel errors. The visibility of channel errors depends strongly on the source encoding algorithms. As an example the minimum bit error rate (BER) for which errors are just noticeable at the display is 10^{-7} for a simple DPCM algorithm (fixed length codewords) ; whereas it falls down to 10^{-10} when this algorithm is followed by variable-length-encoding (VLC) [1].

As a result, for noisy channels applications, it is necessary to correct the channel errors or to devise methods for reducing the effect of errors (techniques of error-concealment). In the field of error control many coding techniques have been studied. These techniques consist of coding the images without taking into account their characteristics, or, on the contrary, combining the source and channel coding by utilizing the properties of images. In this last case many techniques have been investigated [2-3]. Modestino et al [2] use the principle of finding a trade-off between source and channel coding, when the source encoder under study is based on the discrete-cosine-transform (DCT), and a fixed number of bits allocated to each transformed block (no VLC). By applying convolutional and block codes (all with low coding rate), they consider three different selective protection options (information bits which are related to the DCT coefficients are coded in three different ways) for a large set of encoder and decoder pairs. Using the same principle, Gomstock and Gibson [3] by estimating the more important bits of the DCT blocks to be protected, evaluate the performance of some Hamming codes. Since these techniques consume a part of the available bit rate as parity check bits for the more important coefficients of the DCT block, a performance degradation is expected. However this performance degradation is much smaller than the one expected if no protection is performed (when errors occur).

The purpose of this paper is to investigate combined source-channel encoding with a small amount of extra redundancy (⩽ 11 %), where the source encoder is based on the DCT, adaptive quantization and variable length encoding. The channel encoder is based on the unequal-error-protection (U.E.P) codes, where only one encoder-decoder is required to achieve different levels of protection in the transmission message word. The main important functions of the source encoder under study, the influence of channel errors on the picture quality and the error sensitivity factor of each bit (i.e.the measure of importance of each bit) in the variable length coded frames (i.e. DCT block coefficients coded in VLC), are described in section II. The optimal bit error rates (i.e. the optimal error-protection levels) required for each bit in the transmitted frame is discussed in section III. In section IV by reviewing briefly the U.E.P. codes and an interesting way of constructing them, Blokh-Zyablov (BZ) code construction, we bring-out some constraints imposed by the characteristics of the source encoder frames (i.e. frames with variable length, and good synchronization properties). Finally examples and numerical results are given and discussed in section V. Particular attention is paid to the number of levels of protection required for the U.E.P. codes to attain optimal performances.

II. SOURCE CODING ALGORITHM AND INFLUENCE OF TRANSMISSION ERRORS

a) Source coding algorithm

To reduce the raw bit rate of digital images, different coding algorithms have been studied. For limited bandwidth channels, the performance measurement of such a coding scheme depends on its compression factor, the signal to noise power ratio (SNR) at the decoder side and

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the subjective quality of the reconstructed picture (a reasonable SNR is not on its own a guarantee of good picture quality).

One of the most attractive schemes possessing a high performance is based on the Discrete-Cosine-Transform (DCT) [4], whose block diagram is given in fig. 1. Let's briefly look at the more important functions of this scheme:

- the picture is divided into small blocks of (NxN) pixels, and each block is submitted to the DCT. Let f(j, k) j, k = 0,.., n-1 denote the amplitudes of the pixels before transformation. The bidimensional DCT is then defined by :

$$F(u,v)=\frac{4c(u)c(v)}{N}\sum_{j}\sum_{k=0,..N-1} f(j,k)\cos\left\{\frac{(2j+1)u\pi}{2N}\right\}\cos\left\{\frac{(2k+1)v\pi}{2N}\right\}$$

$$u,v = 0,..\ N-1, \text{ and } C(\omega) = \begin{cases}\frac{1}{\sqrt{2}} & \text{for } \omega = 0\\ 1 & \text{elsewhere}\end{cases}$$

- these transformed samples are quantized. The quantization step varies according to the activity of the block and to the frequency, in order to limit the visiblity of the coding noise ;
- finally the quantized values (except DC component F(0, 0)) are coded using variable-length-coding to minimize the output bit rate without loss of information. As this process generates a variable output bit rate, a buffer memory is incorporated, combined with a regulation mechanism, reacting on the quantizer, to match the fixed bit rate requirement of the channel.
  To further improve the efficiency of the scheme, one can perform the statistical coding (VLC) on several adjacent blocks multiplexed on a coefficient basis. Thus spatial correlation can be taken into account to reduce the number of bits devoted to the DC components. The bit stream is obtained by combining 4 adjacent blocks (1 quad-block) in the following way (fig. 2a) : 9 bits which are reserved for the DC component of the first block, 4 x 2 bits for the activities of 4 blocks, followed by the differences between the remaining DC components and the 1st DC component, and completed by the variable-length codewords corresponding to the other coefficients of the blocks previously scanned in a zig-zag order and multiplexed. Because this frame contains a variable number of values (zeros are run length coded), a special separation pattern (End Of Block = EOB) belonging to the Huffman table is inserted.

  This coding algorithm achieves a high performance for various sequences of image. In the absence of channel errors, the SNR is greater than 34 dB for a bit rate of 1 bit/pixel. Let's look at the performances degradation of this algorithm in the presence of channel errors in the next sections.

b) **Influence of channel errors**

As was mentioned in the introduction, the higher the compression factor, the greater the significance of the transmitted information and hence the greater the effects of errors.

In practice, channel errors cause more degradation than the bit rate reduction. In addition visibility of channel errors depends strongly on the source encoder algorithm. For the encoder under study, by taking the EOB as the synchronization pattern, we can point out the following events in the presence of channel errors :

- If the errors occur in the fixed length part of the frame, the visibility of the corresponding defects is proportional to the significance of the corrupted information (for instance an error in the most significant bits of the DC component would dramatically modify the whole block).
- If the errors occur in the variable length part of the stream a correct segmentation is no longer garanteed. It may be recovered if a self-synchronization code [5] is used, but it doesn't prevent from merging 2 frames (or more if the synchronization patterns themselves are wrong) into one. It induces some spatial shift that is unacceptable from a subjective point of view. To solve the problem, a new framing will be discussed in section IV.

Assuming a good synchronization, the importance of each bit in the transmitted frames can be quantized by its sensitivity to channel errors.

c) **Error sensitivity of each bit**

The approach described here to measure the sensitivity of each bit to the channel errors is similar to the intuitive approach which has been developed by J. Hagenaurer et al [6]. It takes benefit of the following remark : each bit of the bit stream has to be protected proportionnaly to its influence on the SNR when corrupted by an error. Levels of protection and hence error probabilities of the bits are adjusted so that their respective contribution (sensitivity) to the overall noise power, weighted by their error probabilities, are equal. This condition leads to an optimal set of parameters.

More precisely, the SNR for a given image in the presence of channel errors is given by : $SNR = 10\log\left(\frac{P_{SM}}{P_N}\right)$ where P_{SM} is defined as the theoretical maximal power of the image and P_N represents the noise power. Then P_N is given by :

$$P_N = \sum_{i=1}^{M}\sum_{k=1}^{4N^2}\left(x^i(k) - \hat{x}^i(k)_e\right)^2$$

Where M and N^2 are respectively the number of quadblock (4 adjacent blocks) in the image and the number of pixels in each block.
Where $x^i(k)$ represents the k^{th} pixel amplitude of the i^{th} block before encoding and $\hat{x}^i(k)_e$ the k^{th} pixel amplitude of the i^{th} block after decoding, in the presence of channel errors. If there is no channel error $\hat{x}^i(k)_e = \hat{x}^i(k)$ and $(\hat{x}^i(k)_e - \hat{x}^i(k))$ represents the source coding noise.

Let l_i be the length of coded frame i, then the number of error patterns will be 2^{l_i}.

Assuming independence of error patterns from frame to frame, the noise power can be expressed as :

$$P_N = \sum_{i=1}^{M}\sum_{k=1}^{4N^2} \varepsilon_q^2(k,i) + \sum_{i=1}^{M}\sum_{e=1}^{2^{li}} P_e \times$$

$$\left(\sum_{k=1}^{4N^2} \varepsilon_c^2(k,i)+2\,\varepsilon_c(k,i)\times\varepsilon_q(k,i)\right)$$

where :

$$\begin{cases}\varepsilon_q(k,i) = x^i(k) - \hat{x}^i(k)\\ \varepsilon_c(k,i) = \hat{x}^i(k) - \hat{x}^i(k)_e\end{cases}$$

and P_e is the probability of the e^{th} error pattern.

The P_N can be written as :

$$PN = P_{Nq} + P_{NC}$$

where : $P_{nq} = \sum_{i=1}^{N}\sum_{k=1}^{4N^2} \varepsilon_q^2(k,i)$,

which is the source coding noise.

$$P_{NC} = \sum_{i=1}^{M}\sum_{e=1}^{2^{li}} P_e A_e^i ,$$

$$A_e^i = \sum_{k=1}^{4N^2} \varepsilon_c^2(k,i)+2\,\varepsilon_c(k,i)\times\varepsilon_q(k,i)$$

P_{NC} depends on the channel errors, and it can be considered as the sum of channel noise and the interaction of source coding-channel noises.

Assuming that we can neglect the effect of error patterns of weight > 1 after correction, then P_{NC} can be written as :

$$P_{NC} = \sum_{i=1}^{M}\sum_{j=1}^{li} P_j A_j^i$$

where P_j is the probability of error in the j^{th} bit (P_j doesn't depend on the frame) and A^i_j is the noise power due to an error on bit j of block i.

P_{NC} can be rewritten as :

$$P_{NC} \simeq \sum_{j=1}^{l_{max}} P_j \sum_{i=1}^{M} A_j^i = \sum_{j=1}^{l_{max}} P_j \overline{A_j} \qquad (I)$$

Where l_{max} is the maximal frame-length value and A_j the average contribution of an error on bit j on any block.

From previous formula (I), the sensitivity of bit j can be derived :

$$(SNR)_j = 10 \log \frac{P_{SM}}{P_{Nq} + \overline{A}_j} \qquad j = 1,\dots l_{max}$$

that is obtained by systematicaly putting an error at the j^{th} bit position of all frames.

A curve of sensitivity has been plotted for "Girl" TV sequences in fig. 4 that is in agreement with expectations of previous section. Optimal set of bit error rates P_j is evaluated in the next section.

III. OPTIMAL BIT ERROR RATE REQUIRED FOR EACH BIT OF THE TRANSMITTED FRAME

As was discussed before, the SNR of an image, in the presence of errors depends strongly on the bit error rate for each bit. To determine the optimal BER for each bit that achieves a high SNR, it is desirable to fulfil the following condition : $P_{NC} = K \ll P$, where P is the channel noise and P_{Nq} is the source coding noise.

We can choose a set of P_j so that all contribution to noise power are equal. This choice driven by intuition is proved to minimize a criterion strongly related to the overall redundancy.

It yields : $P_{NC} = l_{max} P_j\overline{A}_j = K, j = 1,\dots l_{max}$

or $P_j = \dfrac{K'}{\overline{A}_j}$; $K' = \dfrac{K}{l_{max}}$

where K is a predefined constant.

So to respect the above condition, we have to equalize the curve of sensitivity factor. Let's consider the example of "Girl", the bit error rate required for each bit is given in fig. 6. It corroborates our fieling that the first bits (corresponding to low order DCT coefficients) need more protection than the last bits (corresponding to high order DCT coefficients). Although, in case of error, segmentation is no longer correct until the end of the frame, the last bits do not contribute a lot either to signal to noise ratio or to subjective quality (the human eye is less sensitive to high frequency part).

IV. APPLICATION OF U.E.P. CODES

a) Unequal-error-protection codes

In many applications it is desirable to provide different protection levels for differents components m_i of the message word m. Linear codes that provide a greater amount of protection for certain positions than for others are called unequal-error-protection codes [7-11].

A suitable measure of these protection-levels for different positions in a message word is the so called separation-vector [8]:

Definition : For a linear (n,k) code C over the alphabet GF(q), the separation vector $S(G) = (S(G)_1, S(G)_2 \dots S(G)_k)$ with respect to a generator matrix G of C is defined by

$S(G)_i = \min \{wt(mG)/m \in GF(q)^k,\ m_i \neq 0\}, i = 1,\dots k$

where wt (•) denotes the Hamming weight function.

If $S(G)_i = S(G)_j$ $\forall i, j = 1,$ K, then, the code is an equal-error-protection.

The minimum distance of the code is $d_{min} = \min (S(G)\ i), i = 1, \dots k.$

The error-correction capability of a code, when we use a q-ary symmetric channel is given by

Theorem 1 [9]: A linear code C over GF(q), with generator matrix G and complete maximum likelihood decoding, guarantees the correct interpretation of the i^{th} message digit, whenever the error pattern weight is less or equal to $\dfrac{S(G)_i-1}{2}$.

A basic problem is to find an U.E.P. code with a given dimension and separation vector such that its information rate is maximal. Different construction methods have been studied [9] [11]. An interesting one is based on the Blokh-Zyablov (BZ) construction [11]. We will now examine this constructing method :

Blokh-Zyablov (BZ) U.E.P. code construction [11] (fig. 2b)

Let B_i be a (n, k_i, d_i) linear code over $GF(2^{ai})$, with a generator matrix G_i and minimum distance d_i, for i = 1, ..r Let G be a generator matrix for a C(N, K) code, where $K = \sum_1 a_i$, and let $m = (m1, m2, \dots m_r)$, $m_i \in GF(2^{ai})^{ki}$ be the i^{th} components of the message m. Then the BZ coding process is as follows :

- the m_i, $i = 1...r$, is coded by the code B_i : $C_i = m_i G_i$,
- then C_i is arranged in the i^{th} block (a_i lines and n columns) of nxK matrix M where each column of i^{th} block is the binary representation of symbols of C_i,
- finally the complete matrix M is coded by G and gives the BZ codewords : $C = G^T M$.

The resulting code is a two dimensional (N, n) code of length nN and

rate $R = \frac{\sum_{i=1}^{r} a_i k_i}{nK}$.

Let ei (i = 1, ...r) denote the minimum distance of the binary code generated by the last (r-i+1) blocks of G, then the U.E.P. capability of the BZ code is derived in the following :

Theorem 2 [11]. The BZ code has a separation vector $(S_1, S_2, ..S_r)$ for the message space (m1,m2, ..mr) that satisfies the following inequalities :

$Si \geq ei.di$ if $d1.e1 \geq d2.e2 \geq dr.er$

From the above construction, we can derive different U.E.P. codes for a given dimension and given code rate. Let's see the application of these codes to image transmission :

b) **Application of U.E.P. to image transmission**

As we saw before the bit stream after the source encoder has different levels of sensitivity to errors, hence an U.E.P. code is required. The two problems encountered in the application of these codes can be stated as follows:

- The length of each frame l_i varies, thus, the U.E.P. code should be adapted to each l_i i.e. variable length U.E.P. codes should be envisaged,
- and finally, if we find an U.E.P. code, taking into account the above mentioned problem, then, the data rate after the coding process will be variable,(the added redundancy varies with respect to l_i) hence, it has to be regulated.

The variability of the frame length imposes a constraint on U.E.P. codes - that of shortening the codewords if $l_i <$ number of information bits available. A code can be shortened if it is a systematic code. One systematic U.E.P. code can be designed by the BZ code construction if the B_i is a systematic code and G has the following form :

$$G = \begin{bmatrix} I & 0 & \\ 1 & 1 & \\ . & & \\ . & & \\ 1 & 0 & 1 \end{bmatrix} \begin{matrix} a_1 \\ a_2 \\ a_r \\ \\ \\ \end{matrix}$$

here $e_1 = 1$, $e_2 = e_3 ... e_r = 2$ and I is the $a_1 \times a_1$ identify matrix

However the class of code possessing the above properties is limited and does not have optimal performance, nevertheless it solves the problem of frame-length variability and has a very simple decoding process.

To regulate the data rate, one can use the same principle as used for regulating the information data rate after the source encoder i.e. to incorporate a supplementary buffer memory, combined with a regulation mechanism reacting on the U.E.P code. But the system complexity (for encoding and decoding) prohibits such a solution. An alternative solution consists of using a common buffer memory (fig. 3) for source-channel encoders. The feedback will be the same as the source encoder (i.e. controlling the quantization step).

As mentioned in section II, the synchronisation between frames have to be absolutly guaranteed to avoid any spatial shift in the picture. Since the U.E.P. coding process modifies the VLC data stream the utilization of EOB (a VLC word) as the synchronization pattern, doesn't allow to assure a synchronization between frames. To overcome this problem, the solution proposed here is to transmit the frame length l_i in order to separate the frames. To increase robustness of the system, this frame lengths are also protected so that synchronisation recovery is highly improved for critical channel BER values. It has to be noted that an inimitable pattern is regularly inserted (between each 16 quad-block) to limit error propagation.

To illustrate the application of these codes to some sequences of images, we will give some examples and dicuss the simulation results in the following.

V. EXAMPLES AND SIMULATION RESULTS

As was stated in the introduction, the purpose of this study is to define a combined source-channel encoding (with small amount of extra redundancy), and to investigate the performance of U.E.P. codes in the case of random errors (Binary Symmetric Channel : BSC). Two sequences of images : "Girl" and "Baltimore" are coded with the source-encoder described in section II (block size 8x8 ; bit rate 1 bit/pixel). The error sensitivity factor of each bit in the coded variable-length frame is measured for each sequence and is represented in Fig. 4. These curves have approximately the same shape and show that the SNR depends strongly on the position of erroneous bits in the transmitted frames.

The set of P_j is calculated as indicated in section III for a constant K equal to 10^{-5}. The error sensitivity factors reordered in an increasing manner (fig. 5), the optimal error rate for each bit is represented in Fig. 6. As shown by these curves, the first bits of each ordered frame have to be protected to give an error rate of around 10^{-9}, while the last ones dont require any protection, if the channel bit error rate is less than 10^{-2}. Hence different levels of protection are required.

The frame-length, which is the most important information, has to be protected very efficiently. Four frame-lengths are gathered and coded by a binary C(57, 40) shortened cyclic code. If the channel bit error rate is 10^{-4}, then bit error rate after decoding for the synchronization word is 10^{-12}, which is a reasonable value.

To protect the information of the frames against channel errors, two U.E.P. codes are designed. These codes, which are constructed by the Blokh-Zyablov construction method have respectively $(7^{45}, 5^{366}, 3^{372})$ (code 1) and $(5^{354}, 3^{372})$ (code 2) separation vectors. As these vectors show, the first code has three levels of protection (the average redundancy R of the whole channel encoder (the frame-length and the U.E.P. protection bits) is 11 %) while the second code has two levels of protection (R = 10 %). The B_i codes used to construct these U.E.P. codes are summarized in table 1. The performance of these

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