pulses is modulated by the THz field. The photocurrent associated with the battery (DC field) is not modulated, and therefore it can be filtered out by a lock-in amplifier, whereas the signal is extracted. It should also be noted that the difference between the pump and probe pulses relies only on their relative timing. Whichever comes earlier serves as the pump pulse.

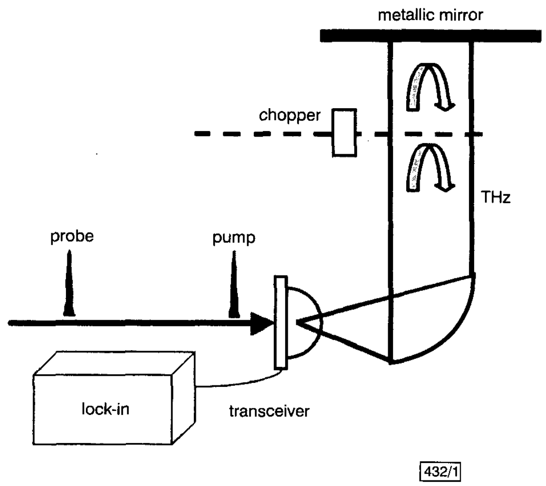

Fig. 1 *Schematic experimental setup of THz transceiver*

THz signal is generated and detected by same photoconductive dipole antenna (emitter-receiver); transceiver is attached to a silicon lens

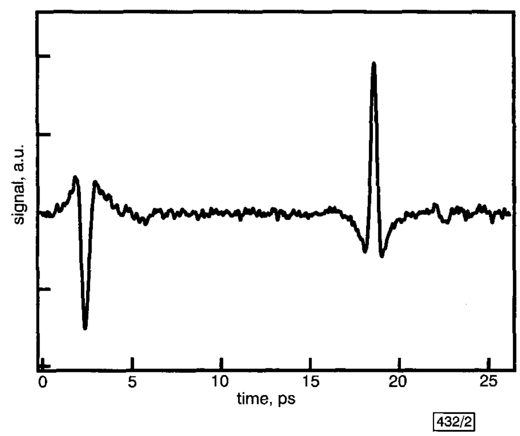

Fig. 2 *Temporal waveform of returned THz signal*

First inverted signal is reflection from metallic chopper blade, and second peak is returned signal from metallic mirror

Fig. 2 shows a plot of the measured temporal waveform of the returned THz signal. The first signal (left) is the THz reflection from the metallic chopper blade once the chopper blade was set to be perpendicular to the propagation direction of the THz beam, and the second peak is the THz signal transmitted through the chopper but reflected back from the metallic mirror. Because there is a π phase difference between the phases of the transmitted and reflected THz beam from the chopper blade (compared to the chopper reference and measured with the lock-in amplifier), these two signals reflected from the chopper and the mirror show opposite polarities. The time delay between two THz signals is the round trip time of a THz pulse which has travelled between the chopper and the metallic mirror. The reflection from the chopper blade automatically serves as a reference marker for the system calibration.

Because the photocurrent generated by the optical beams (both pump and probe) and the bias voltage contributes to the noise, the measured THz waveform has a signal-to-noise ratio (SNR) of 200. Nevertheless, with better selection of the filtering circuit and operational conditions (such as a modulation frequency of several kilohertz), we expect a substantial improvement in the SNR. A noise characterisation and analysis are currently being carried out.

The experimental setup shown in Fig. 1 is simplified compared to that of the conventional THz system which uses two antennas and two parabolic mirrors. It also has a simplified alignment. The THz transceiver should have unique THz ranging [8] and THz sensing applications. It is also an ideal device for THz imaging and tomography [9] in the reflection configuration. Along with an ultrafast fibre laser and optical fibre connection, the dimensions of the THz spectroscopy and imaging systems can be further reduced.

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M. Tani, Zhiping Jiang and X.-C. Zhang (*Physics Department, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, USA*)

E-mail: zhangxc@rpi.edu

M. Tani: Permanent address: Kansai Advanced Research Center, Communications Research Lab., 588-2 Iwaoka, Kobe, 651-2401, Japan

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Evaluation of transfer functions for punctured turbo codes

A.H. Mugaibel and M.A. Kousa

A modified algorithm for evaluating transfer functions of turbo codes with punctured systematic bits is presented. The obtained transfer function leads to a more accurate estimation of the weight distribution of the code. Consequently, a tighter upper bound on the bit error rate performance of the code is obtained.

Introduction: Turbo codes are attracting the attention of many researchers because of their excellent performance. Owing to the low rate of turbo codes, due to parallel concatenation, there is a genuine reason for puncturing them so as to increase the code rate [1].

The evaluation of turbo codes is usually based on the union bound. The computation of the union bound requires knowledge of the weight distribution of the code which can be inferred from the transfer function. Unfortunately, it is more difficult in general to calculate the transfer function of punctured codes [2].

The usual algorithm for estimating the transfer function, which accounts for puncturing, is based on averaging. However, it has been noticed that when systematic bits are punctured, the averaging approach does not have the provision for tracing the effect of puncturing on the resultant codeword. Alternatively, we have to resort to averaging out this effect on the weight distribution. In this Letter we propose a modification to the averaging technique that results in a more accurate evaluation of the weight distribution of turbo codes when systematic bits are punctured. Consequently a tighter upper bound on the BER of the code is obtained.

Averaging technique: For an input sequence of length k and Hamming weight w, if M bits in a period of p are punctured then the total number of punctured bits is $(k*M/p)$. The weight y of the punctured systematic sequence is then bounded as

$$w - (k * M/p) \leq y \leq w \qquad (1)$$

The averaging algorithm does not have the ability to find the exact value of y for a given w and a particular puncturing pattern. Instead, averaging over the whole frame is carried out to find the probability of having a weight-y output by puncturing a weight-w input, $p(y|w)$. That is, it is assumed that all patterns of $k*M/p$ punctured bits out of the k bits are possible, and that they are all equiprobable.

Based on these assumptions, we have

$$p(y|w) = \frac{C_{w-y}^{k*M/p} * C_y^{k-(k*M/p)}}{C_w^k} \qquad (2)$$

The result is then used to calculate the transfer function of the code.

Modified technique: Recall that for the evaluation of the code performance we need to keep a record of the input weight and the output weight associated with it. When the systematic sequence is not punctured, it is sufficient to know the input weight and the weight of the parity sequence, as the overall output weight is simply the sum of the two. Unfortunately, this is not the case when systematic bits are punctured, and therefore it is essential to keep a record of the weight of the punctured systematic sequence. We propose to modify the format of the transfer function so that it acquires this information.

We define the function D_w^C which keeps a record of the weight of the systematic sequence after puncturing for an input sequence of weight w. It is represented by the following summation:

$$D_w^C(Z, Y) = \sum_{y,j} A_{y,j} Z^j Y^y \qquad (3)$$

where Y and Z are dummy variables, y is the weight of the systematic branch after puncturing, j is the weight of the parity branch and A is the multiplicity (number of codewords with the corresponding weights).

One method for evaluating $D_w^C(Z, Y)$ is to utilise the procedure presented for punctured parity bits. We need to first modify the transition matrix of the first constituent code to account for the variable Y. The variable Y is introduced in the transition matrix by replacing W (where W is a dummy variable with power equivalent to the input weight) by WY. The remaining procedure for evaluating the transfer function is carried out normally, with this modification invoked where appropriate.

Without loss of generality, we now determine the transfer function of a particular turbo code, the (1,5/7,5/7) code, and a particular puncturing matrix. For the (1,5/7) constituent code the modified transition matrix is

$$\mathbf{A}(W, Z, Y) = \begin{pmatrix} 1 & 0 & WZY & 0 \\ WZY & 0 & 1 & 0 \\ 0 & WY & 0 & Z \\ 0 & Z & 0 & WY \end{pmatrix} \qquad (4)$$

Consider the puncturing matrix

$$\mathbf{P} = \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix} \qquad (5)$$

The first row of $\mathbf{P}$ implies that the third systematic symbol in every sub-sequence of three symbols is punctured. The second and third rows are for the parity bits from the first and second encoders, respectively.

We first compute the transition matrix over one period for each constituent code. We take the systematic branch as a part of the first constituent code C_1. For the puncturing matrix in eqn. 5 and for the first constituent code C_1, we obtain

$$\mathbf{B}^{C_1}(W, Z, Y) = \mathbf{A}(W, Z, Y)\mathbf{A}(W, 1, Y)\mathbf{A}(W, Z, 1) \qquad (6)$$

This equation implies that in the first transition both the systematic bit and the parity bit are transmitted, in the second transition the systematic bit is transmitted but the parity bit is punctured, and in the third transition the systematic bit is punctured and the parity bit is transmitted.

Table 1: D_m for (1,5/7,5/7) turbo code and $\mathbf{P}$ = [1 1 0] using averaging and modified techniques

Codeword weight m	D_m using averaging technique	D_m using modified technique
3	0	0
4	0.00001758369	0
5	0.00010925460	0
6	0.00032662980	0.0004947929
7	0.00080264170	0
8	0.00390303700	0.0097513440
9	0.01206679000	0
10	0.01856358000	0.0366604400
11	0.02618730000	0
12	0.03786333000	0.0728424400
13	0.04912956000	0
14	0.07454436000	0.1423494000
15	0.10620620000	0
16	0.17585560000	0.3456495000
17	0.28859980000	0
18	0.51055000000	1.0028360000

For the second constituent code C_2, only parity bits are produced. Therefore, the variable Y should be set to '1', or more conveniently dropped out. According to the third row of $\mathbf{P}$ in eqn. 5, the transition matrix over one period for the second constituent code is given by

$$\mathbf{B}^{C_2}(W, Z) = \mathbf{A}(W, 1)\mathbf{A}(W, Z)\mathbf{A}(W, Z) \qquad (7)$$

The transition matrices for C_1 and C_2 over a frame of length k are then calculated as

$$\mathbf{F}^{C_i}(W, Z, Y) = \mathbf{B}^{C_i}(W, Z, Y)^{k/p} \qquad i = 1, 2 \qquad (8)$$

Finally, the transfer function of the turbo code is obtained by assuming a uniform interleaver as in [3]. It should be noted that once $\mathbf{B}^{C_1}$ and $\mathbf{B}^{C_2}$ are formulated, the contribution of the punctured systematic and parity branches to the overall output weight need not be distinguished. Therefore, both variables Z and Y may be replaced by one variable, say H. This will simplify the calculation of the frame transition matrix $\mathbf{F}^{C_1}(W, Z, Y)$ which will now be a function of two variables W and H, with the power of the variable H carrying the overall output weight, i.e. systematic and parity, for the first constituent code.

Comparison of the two techniques: We now apply the two methods to find the weight distribution of the (1,5/7,5/7) turbo code where only systematic bits are punctured. The systematic sequence is punctured according to the vector [1 1 0], that is $p = 3$ and $M = 1$. Table 1 shows the weight distribution D_m of the turbo code using the averaging method and the modified method up to weight m = 18, where D_m is defined as

$$D_m = \sum_{j+w=m} \frac{w}{k} A_{w,j} \qquad (9)$$

The accuracy of our approach in estimating the weight distribution is quite evident. In particular, the numerical results show that

(i) the minimum distance of the code cannot be less than 6
(ii) odd-weight codewords do not exist.

This added accuracy in estimating the minimum distance and the weight distribution of the code leads to the computation of a tighter bound on the BER performance. Fig. 1 shows a comparison between the bounds using the averaging technique and that using the modified technique for the (1,5/7,5/7) turbo code. Two puncturing patterns of the systematic sequence are considered. In the first case, one systematic bit is punctured in a period of two ($M = 1$, $p = 2$), while in the second case one systematic bit is punctured in a period of three ($M = 1$, $p = 3$).

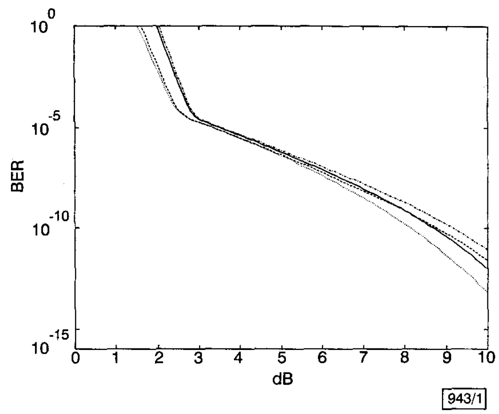

Fig. 1 *Comparison of upper bound on BER using averaging and modified techniques*

— · — averaging [3], $M = 1$, $p = 2$
– – – – averaging [3], $M = 1$, $p = 3$
·········· modified [1 1 0]
——— modified [1 0]

The improved tightness of the bound at high values of E_b/N_0 due to the modification is quite evident. The reason behind this can be explained as follows. Over this range of E_b/N_0, the code performance is dominated by the minimum distance of the code. The averaging method estimates the minimum distance of the code to be 4, while the actual minimum distance of the code, as learned from the modified technique, cannot be less than 6. The averaging method assumes the presence of all possible combinations of the two constituent code outputs with different probabilities. This includes associating low weight codewords from both constituent codes even though they might not exist.

There is another significant advantage of the modified technique: it permits the investigation of different puncturing patterns when systematic bits are involved. The averaging technique does not have this freedom, and as long as the puncturing patterns have the same p and M, then the same weight distribution will be obtained. In addition, the modified technique helps in investigating the effect of puncturing systematic symbols compared to puncturing parity symbols, which is also not possible using the averaging technique.

Conclusion: A modified technique for evaluating the weight distribution for punctured systematic bits has been shown to result in a better estimation of the minimum distance, a more accurate evaluation of the weight distribution and a tighter BER performance curve of the code compared to the averaging technique. Also, the modified technique has an added analytical value as it enables the investigation of different patterns of puncturing systematic bits.

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A.H. Mugaibel and M.A. Kousa (*EE Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, PO Box 1721, Saudi Arabia*)

E-mail: mugaibel@kfupm.edu.sa

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Importance of quantiser design compared to optimal multigrid motion estimation in video coding

J. Malo, F.J. Ferri, J. Gutierrez and I. Epifanio

Adaptive flow computation and DCT quantisation play complementary roles in motion compensated video coding schemes. Since the introduction of the intuitive entropy-constrained motion estimation of Dufaux *et al.*, several optimal variable-size block matching algorithms have been proposed. Many of these approaches put forward their intrinsic optimality, but the corresponding visual effect has not been explored. The relative importance of optimal multigrid motion estimation with regard to quantisation is addressed in the context of MPEG-like coding. It is shown that while simpler (suboptimal) motion estimates give subjective results as good as the optimal motion estimates, small enhancements in the quantiser have significant visual effects. This suggests that more attention should be paid to the quantiser design.

Introduction: In H.263 and MPEG video coders, the original sequence is split into two lower complexity signals that carry information about motion and prediction errors. These are referred to as the displacement vector field (DVF) and the displaced frame difference (DFD). A more complex and accurate DVF gives rise to a better prediction (lower complexity DFD). However, the relative effectiveness of such a detailed description relies heavily on the DCT quantiser used. In other words, the better the quantiser, the less significant the improvement due to motion estimation.

The so-called entropy-constrained multigrid approach [1] explicitly makes use of this trade-off between motion estimation and DFD complexity. Since this approach was introduced, great effort has been devoted to obtaining analytical [2 – 4] or numerical [5] optimal entropy-constrained quadtree DVF decompositions. These approaches criticise the (faster) entropy measure of the DFD in the spatial domain of Dufaux *et al.* because it does not take into account the effect of the selective DCT quantiser. This necessarily implies a suboptimal bit allocation between DVF and DFD. The literature [2 – 5] reports the quantitative optimality of the proposed methods, but the practical (subjective) effect of this gain on the reconstructed sequence is not analysed. In particular, only (perceptually unweighted) SNR or MSE distortion measures are given and no explicit comparison of the decoded sequences is shown.

In this Letter, the relative importance of an optimal adaptive motion estimation is addressed. Combinations of variable-size block matching algorithms (VSBMAs) [1, 5] and different quantisation schemes [6 – 8] are evaluated. Distortion results with perceptually meaningful measures [9, 10] and explicit comparisons of the reconstructed frames are shown.

Algorithms and distortion measures: Two different approaches can be followed to design VSBMAs. First, the final bit-rate can be optimised taking into account both adaptive motion and error encoding [2 – 4], given a particular coding scheme. Second, a splitting criterion which is related to the entropy of both motion and error signals can be used for adaptive motion estimation [1, 5]. In the latter case, the corresponding VSBMAs locally increase the resolution if the volume of the resulting signal is reduced, i.e. a block is split if $H(DVF_{split}) + H(DFD_{split}) < H(DVF_{nosplit}) +$