TRANSRATING OF MPEG-2 CODED VIDEO VIA REQUANTIZATION WITH OPTIMAL TRELLIS-BASED DCT COEFFICIENTS MODIFICATION

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ABSTRACT

Requantization is one of the tools for bit-rate reduction of pre-encoded video to adapt it to various network bandwidth constraints. Several recent works propose using Lagrangian optimization to find the optimal quantization step for each coded macro-block, to meet a desired rate at minimum distortion. In this paper we propose to extend the Lagrangian optimization procedure by allowing the modification of quantized coefficients values, including setting their values to zero, in addition to quantization step-size selection. Coefficient value modification and quantization step-size selection are optimally done using a low complexity trellis-based procedure. The proposed requantization algorithm provides higher PSNR values than the Lagrangian-based optimization method that only handles the selection of quantization steps, and still does not exceed considerably its complexity.

1. INTRODUCTION

Transrating of MPEG-2 coded video aims at reducing the bit-rate of the encoded stream in situations like channel congestion, or matching the encoded video bit stream rate to a low bit rate destination, while preserving the highest possible quality of the rate-reduced video. A common approach for bit-rate reduction, in the compressed domain, is requantization by increasing the quantization step-size of the Discrete Cosine Transform (DCT) coefficients in each block. Several works propose very low complexity open-loop transcoding [6, 7], while other take the advantage of error compensation provided by a closed-loop scheme [1, 5]. Instead of "simple" requantization, which applies the standard complexity model and rate control of TM5 to set a new quantization step-size for each macro-block (MB), several recent works propose using Lagrangian optimization for finding the optimal quantization step for each MB to meet a desired bit-rate at minimum distortion [2, 1]. It is shown in [1] that the optimally transrated bit stream provides a higher peak-signal-to-nose-ratio (PSNR) than a cascade of decoder-encoder (i.e., re-encoding of the decoded video to the reduced bit-rate), and can even provide a better video quality than the standard TM5 encoder applied to the original video sequence at the reduced rate. Lagrangian optimization was also used recently for discarding certain quantized coefficients in I-frames [6]. In this paper we propose to extend the Lagrangian optimization procedure by allowing also the modification of *quantized coefficients values*, including setting their values to zero, in all frame types. The organization of this paper is as follows: Section 2 describes the MPEG-2 encoding procedure. Section 3 presents the pertinent Lagrangian optimization method. In section 4 we introduce the idea of quantized coefficients modification and in section 5 we present its efficient implementation using a trellis diagram. Complexity issues are discussed in section 6. In sections 7 and 8, experimental results are shown and conclusions are presented, respectively.

This work is supported by STRIMM consortium under the MAGNET program of the Ministry of Trade and Industry via the Samuel Neaman Institute.

2. MPEG-2 AC COEFFICIENTS ENCODING

Following the application of the DCT to each of 4 luminance 8*8 blocks and from 2 to 8 chrominance blocks (depending on video format), which form a MB, the DCT coefficients, except for the DC coefficient, are quantized. For each MB, a value from one of two possible tables, each having 32 quantization step-size values, is selected (a different table can be chosen for each frame). The actual quantization step-size used for each coefficient is the product of the selected step-size from the table and a value defined by a suitable quantization matrix that depends on the MB type. The 63 quantized AC coefficients are concatenated in an order defined by one of two possible zig-zag scans. The resulting 6 to 12 vectors, of 63 quantized coefficients each, constituting a MB, are entropy coded by a variable-length coding (VLC) table. Each coefficient vector is divided into several parts, with each part consisting of a *run* of consecutive zeros followed by a non-zero *level* value, defining a run-level pair. In case of adjacent non-zero level values, the run length is defined to be zero. The MPEG-2 standard defines for every run-level pair a variable-length codeword. There are two VLC tables that can be used. It is possible to use the same table for all types of MBs, or to use a different one for Intra MBs [4].

3. REQUANTIZATION VIA LAGRANGIAN OPTIMIZATION

The requantization problem can be formulated as an optimization problem of determining a set of quantization step-sizes that minimize the total distortion in each frame, under a given bit-rate constraint:

$$\min_{\{q_k\}} D, \text{ under the constraint } R \leq R_T \tag{1}$$

with ,

$$D = \sum_{k=1}^{N} d_k(q_k), R = \sum_{k=1}^{N} r_k(q_k), \tag{2}$$

where, N - number of MBs in the frame; q_k - quantization step for the k-th MB; d_k - distortion caused to the k-th MB; r_k - number of bits produced by the k-th requantized MB.

An analysis for the conventional MSE distortion metric is presented in [1]. The problem can be converted into an unconstrained one by merging rate and distortion through a Lagrange multiplier $\lambda \geq 0$ into the cost function:

$$J_{total} = D + \lambda R \quad (3)$$

λ defines the relative importance of rate against distortion in the optimization procedure. The Lagrangian cost can be independently calculated for each MB. Thus, for the k-th MB:

$$J_k(\lambda) = \min_{q_k}\{d_k(q_k) + \lambda r_k(q_k)\} \quad (4)$$

The particular value of λ, denoted λ_s, which provides the desired total bit-rate, i.e., $\sum_{k=1}^{N} r_k(\lambda_s) = R_T$, needs to be found. This is typically done by a search procedure for every frame, if the problem is solved on a frame level, or for every slice, if bit-rate allocation is provided on that level.The set $\{q_k(\lambda_s)\}_{k=1}^{N}$ is the optimal set of quantization step-sizes that provides the minimum distortion for the given total rate constraint, R_T.

4. QUANTIZED DCT COEFFICIENTS MODIFICATION

The idea of modifying the levels of quantized DCT coefficients, before applying VLC, for bit-rate reduction was proposed in [6, 3]. However, [6] discusses only methods for excluding AC coefficients in I-frames, and [3] considers only discarding several last non-zero coefficients in the zig-zag scan. In this work we propose to extend the Lagrangian optimization presented in the previous section to include the possible modification of the values of all quantized DCT coefficients in an efficient way. The suggested optimization procedure aims at selecting quantized DCT coefficient values, as well as optimal quantization step sizes, that will provide a bit-rate that is as close as possible to the desired one, with minimal distortion.

As in the optimization problem stated in section 3, we may select a different quantization step-size for each MB, but here we also allow changing the quantized DCT coefficient value *by modifying its level (quantization index) value* after a particular quantization step-size has been applied. The minimization problem stated in Eq. (1) remains the same, but now (2) is replaced by:

$$D = \sum_{k=1}^{N} d_k(q_k, \mathbf{v}_k), R = \sum_{k=1}^{N} r_k(q_k, \mathbf{v}_k), \quad (5)$$

where $\mathbf{v}_k$ denotes the index vector obtained by rounding the result of dividing the value of each DCT coefficient by the quantization step-size. All other parameters remain the same as in Eq. (2). Note that this formulation can be also applied to the initial encoding of the original data. The problem is still separable at the MB level - like in (4). But now, for every q_k, an additional minimization over all possible $\mathbf{v}_k$ values must be performed. Thus, for the k-th MB, Eq. (4) takes the form of:

$$J_k(\lambda) = \min_{q_k}\min_{\mathbf{v}_k}\{d_k(q_k, \mathbf{v}_k) + \lambda r_k(\mathbf{v}_k)\}, \quad (6)$$

and the set $\{\mathbf{v}_k(\lambda_s)\}_{k=1}^{N}$ is the optimal set of quantized vectors that provides the minimum distortion for a given total rate constraint, R_T. Here r_k depends explicitly only on the index vector $\mathbf{v}_k$, and not on the initial DCT values. An efficient solution for the stated problem is proposed in the next section.

For clarification, and to demonstrate the effect of modifying a run-level pair, let (00000,5) be the run-level pair to be encoded by the MPEG-2 VLC table, and assume that the distortion is measured relative to it. From the VLC table, the number of bits needed to encoded this pair is 24. If we split (00000,5) into two parts (0000,1) and (5), then the number of bits needed to encode each part is 7 and 6 bits, respectively. Thus, the number of bits is reduced by 11, while the distortion is increased by 1 (multiplied by the square of the corresponding quantization step-size), showing that a relatively large reduction in rate can sometimes be obtained by allowing a modest increase in distortion.

To minimize the total cost function value for particular values of λ and q_k, every run-level pair in a coded block may need to be modified. To get the actual distortion, the square of the difference between de-quantized values must be taken. For each value of λ examined, the total-cost value has to be calculated for every value of q_k, and the minimal cost will determine the optimal quantization step-size, as well as the optimal quantized coefficients index vector to be encoded by the VLC table. A search over suitable values of λ need to be done to find the value of λ for which the final bit-rate constraint R_T is met.

5. TRELLIS-BASED OPTIMIZATION

In this section a Trellis-based implementation of the above Lagrangian optimization procedure is discussed.

Let's define each location in the zig-zag scanned quantized DCT coefficients vector as a different stage in a trellis (Fig. 1). The cost value of a path is the sum of the costs of run-level pairs defined by this path. The optimal path up to a particular stage is the path that has the minimal cost value over all possible paths ending at that stage. The essence of a trellis-based algorithm is the fact that minimization of the cost value at each state of the current stage is the minimization of the sum of the current stage local-cost at each state and the minimal path cost already calculated at the previous stages of the trellis. It turns out that for the current problem, where different run-lengths need to be considered, the conventional trellis needs to be modified, so that every decision in a given stage does depend on previous stages, but luckily only on a single, already determined, state in each previous stage, as described below.

Fig. 1 shows how the cost function is evaluated for a particular stage in the trellis. For trellis stage i (corresponding to the i-th coefficient) we have states from zero to $v\_max(i)$. $v\_max(i)$ is determined by multiplying the original index value by the initial quantization step-size, and dividing by the new one, followed by rounding upwards. In general, every possible v, $0 < v \leq v\_max(i)$, should be examined to see if it minimizes the total cost function $J(v,i)$ in Eq. (7) below. This cost depends not only on the value of v, but also on the number of zeros, i.e., the *run* leading to it, which defines the run-level pair for the VLC:

$$J(v,i) = \min_{run}\{J\_min(i - run - 1) + \sum_{j=i-run}^{i-1} D_0(j) + \lambda R(run, v) + D(v,i)\} \quad (7)$$

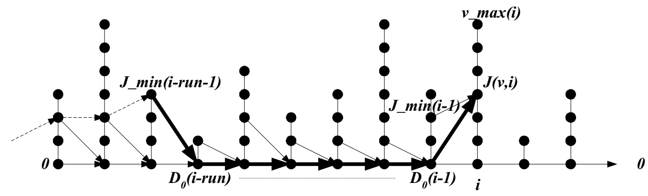

Figure 1: Trellis diagram and possible paths leading to the i-th DCT coefficient in the zig-zag scanned quantized coefficients vector.

where,
$J\_min(i-run-1)$ - the cost of the minimal path up to the stage $(i-run-1)$; $D_0(j)$ - the distortion caused by zeroing the j-th AC coefficient; $D(v,i)$ - the distortion introduced by choosing v to be the value of the i-th quantized coefficient; $R(run,v)$ - the number of bits needed to encode the run-level pair (run,v) using the VLC.

The dotted thin line on the left of Fig. 1 shows the minimal path till stage $i-run-1$, which has the minimal cost $J\_min(i-run-1)$. Thin arrows connect the last values of optimal paths in the previous stages to zero; or, in the case of stage $i-1$, directly to the value v in stage i that is being examined. Different run-lengths need to be examined, but for a particular run the optimal state in the preceding stage is already known. The heavy line indicates the optimal path for the particular value of v.To determine the optimal value of v, the minimum over all its possible values of v has to be found:

$$J\_\min(i) = \min_{0<v\leq v\_max(i)} J(v,i) \tag{8}$$

This procedure has to be applied to every block in a particular MB, with every relevant q_k. At the end of processing each MB, for a particular value of λ, the optimal quantization step-size for that λ is chosen :

$$q_{k,opt}(\lambda) = \arg\min_{q_k} \sum_{n=1}^{\text{No. of blocks in MB}} J_n(\lambda, q_k) \tag{9}$$

where, $J_n(\lambda,q_k)$ is the cost of n-th block in the k-th MB. Yet, even when the above trellis is used, the number of calculations needed to perform the optimization is rather high. Hence, in the next subsection we consider ways to speed up the algorithm.

6. COMPLEXITY CONSIDERATIONS

The proposed method needs, in principle, many iterations over a large number of parameter values because: (i) The number of examined runs for every *level* in a particular stage increases with the index value of the DCT coefficient being processed. (ii) All stages, till the stage corresponding to the last non-zero coefficient, in every block, need to be examined. (iii) A separate trellis has to be constructed for every requantization step-size that we wish to examine. (iv) There are several values of v at each stage that need to be examined. (v) Several values of λ need to be tried (in a directed way) before the total rate will match the constraint.

Note, however, that while the number of index values (levels) to be examined at each stage seems to be large at first sight, it is no so in reality. This is because the mean value of the AC coefficients is typically in the range of 30-50. Hence, if the initial quantization step-size is 6, then even on the finest scale there are on average only about 5÷10 values to choose from. When the quantization step is increased, we reach a single value very quickly.

As for searching over different values of λ, applying a simple bi-section search, as in [1], requires on average about 3 iterations only.

6.1 Complexity Reduction Means

Here we present a number of ways to reduce the number of calculations needed in the proposed Trellis optimization.

1. As mentioned above in (i), the number of examined runs for every *level* in a particular stage increases with the index value of DCT coefficient being processed. We have observed that, practically, the number of level values that should be considered for obtaining a rate reduction is actually not that large. Moreover, if we consider choosing a run for a particular level v, the number of options to examine - $run_{max}(v)$, before getting to the maximum no. of bits in the VLC table, $R_{max} = 24$, is very small for all levels (except for level values 1 and 2, for which there are 31 and 16 possible runs, respectively). Thus, Eq. (7) can be rewritten as follows:

$$J(v,i) = \min\left\{\left(J^{opt}(v,i), J_{opt}(run_{max}(v),i) + \lambda R_{max}\right)\right\} + D(v,i) \tag{10}$$

where,

$$J^{opt}(v,i) = \min_{run<run_{max}(v)} \{J\_min(i-run-1) + \sum_{j=i-run}^{i-1} D_0(j) + \lambda R(run,v)\} \tag{11}$$

and,

$$J_{opt}(run_{max}(v),i) = D_0(i-1) + \min_{run>run_{max}(v)} \{J\_min(i-run-1) + \sum_{j=i-run}^{i-2} D_0(j)\} = J_{opt}(run_{max}(v)-1,i-1) + D_0(i-1) \tag{12}$$

To calculate $J^{opt}(v,i)$, $run_{max}(v)$ iterations are needed, while $run_{max}(v)$ is usually a small number. $J_{opt}(run_{max}(v)-1,i-1)$ is known from the last stage, so no search needs to be done to find $J_{opt}(run_{max}(v),i)$. So, to get $J(v,i)$, only $run_{max}(v)+1$ calculations need to be performed. Using Eq. (10), (11), (12) instead of Eq. (7) *does not affect the optimality of the solution*, but reduces the number of calculations needed by up to 40% in our simulations.

2. Again, as mentioned above in (ii), all stages, till the stage corresponding to the last non-zero coefficient in every block, need to be examined. The simplification proposed here results in a *sub-optimal* solution but with only a slight reduction in performance. As mentioned in Section 4, it may be useful, sometimes, to split a run-level pair into two smaller ones. If no splitting is allowed, the trellis paths need to go through stages defined by the initial non-zero coefficients only. In typical MPEG-2 encoded blocks, about 70% to 90% of the coefficients are zero, so that the computational complexity reduction is very pronounced (may reach 60÷70%). In our simulations, applying this simplification, resulted in a PSNR reduction of just 0.07 dB.

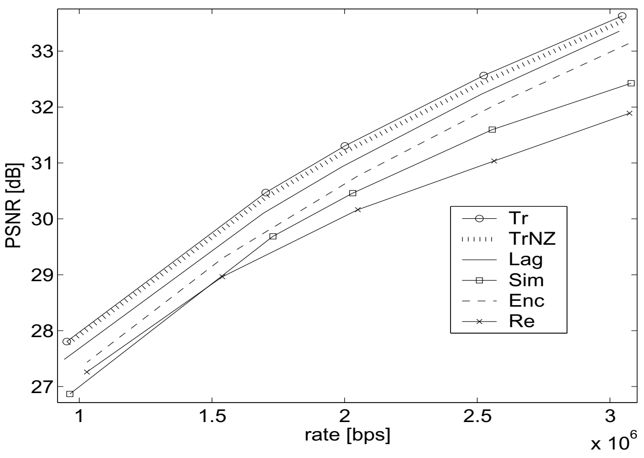

Figure 2: Average PSNR vs. rate for FOOTBALL sequence transrated from 4Mbps into lower rates.

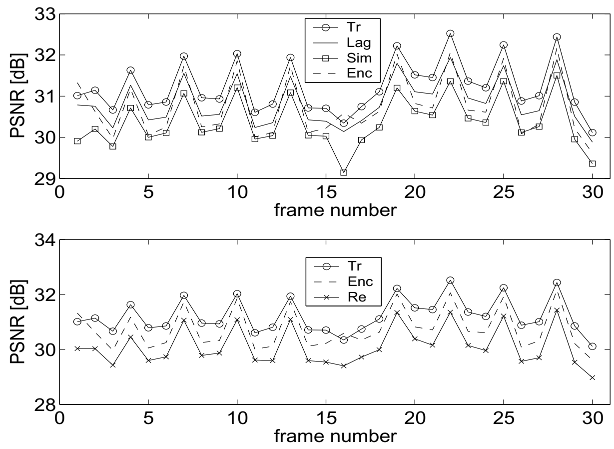

Figure 3: PSNR as function of frame number for FOOTBALL sequence transrated from 4Mbps into 2Mbps.

7. EXPERIMENTAL RESULTS

In this section we compare the performance of the proposed scheme to several other transrating schemes. Because of space limitations we report the results obtained just for the video sequence FOOTBALL (in SIF 4:2:0 format, 45 frames). The sequence was encoded using a standard TM5 encoder at 4Mbps. This rate was reduced by transrating to rates varying from 3 to 1Mbps. The average PSNR values obtained by each of the following transrating scheme are shown in Fig. 2:

1. ”Simple” requantization that uses TM5’s complexity model to transrate each frame (denoted ’Sim’).
2. Lagrangian optimization that finds the optimal set of quantization step-sizes for each frame (’Lag’), like in [1].
3. Proposed Trellis-based optimization (’Tr’).
4. Proposed reduced complexity Trellis-based optimization (’TrNZ’), i.e., trellis paths go through initial non-zero stages only, since no splitting of runs is allowed, as described in 6.1, pt. 2.

The original video sequence and the decoded 4Mbps video were also encoded to the desired bit-rate using a standard TM5 encoder. They are denoted as ’Enc’ and ’Re’, respectively. It is seen from the Fig.2 that ’Tr’ outperforms ’Enc’ at all the rates by about 0.62 dB in average PSNR, while the gain of ’Lag’ over ’Enc’ is only about 0.28 dB. The difference in PSNR between ’Tr’ and ’Sim’ transcoding is about 0.95 dB.’TrNZ’, which is sub-optimal but of reduced complexity, suffers a loss of 0.07 dB as compared to ’Tr’. For other video sequences we got similar results with the proposed Trellis-based schemes, relative to the Lagrangian scheme, while the other methods show more significant variations, but always lower than the proposed Trellis-based schemes. The upper graph in Fig. 3 shows the PSNR for each frame in the FOOTBALL sequence for ’Tr’, ’Lag’ and ’Sim’ transrating schemes, for transrating from 4Mbps to 2Mbps. The results of encoding the original sequence (’Enc’) at 2Mbps is also added for comparison. The lower graph in Fig. 3 shows the performances of ’Enc’, ’Re’ and ’Tr’.

Measuring complexity in terms of run-time, we obtained in our implementation that: ’Lag’ runs 6 times slower than ’Sim’ transrating, and ’Tr’ runs 9 times slower than ’Lag’, while ’TrNZ’ just 3 times slower than ’Lag’.

8. CONCLUSIONS

A Trellis-based Lagrangian optimization for MPEG-2 encoded video transrating is proposed. It is shown that by extending the Lagrangian optimization of quantization step-sizes only, by allowing the modification of quantized AC coefficients, consistently results in better performance than other known schemes, including even those obtained by encoding the original video sequence at the reduced rate with a standard coder. The cost of the proposed scheme is in its complexity. We have shown in this work ways for reducing the complexity and are currently studying further means for complexity reduction.

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