A Buffer-constrained Adaptive Quantization Algorithm for Image Compression

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ABSTRACT

We consider a buffer-constrained adaptive quantization algorithm for image compression. Buffer control algorithm was considered with source coding scheme by some researchers and recently a formal description of the algorithm in terms of rate-distortion has been developed. We propose a buffer control algorithm that incorporates the buffer occupancy into the Lagrange multilplier form in a rate-distortion cost measure. Although the proposed algorithm provides the suboptimal performance as opposed to the optimal Vieterbi algorithm, it can be implemented with very low computaional complexity. In addition stability of this buffer control algorithm has been mentioned briefly using Liapnov stability theory.

버퍼제약에 의한 영상압축 적응양자화 알고리듬

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요 약

본 논문에서는 영상압축을 위한 버퍼 제약에 의한 적응양자화 알고리즘에 대해서 논하고져 한다. 버퍼제약에 의한 알고리즘은 source coding과 더불어 그간 연구되다가, 최근에는 비트율 왜곡의 이름으로 연구가 더욱 진전돼 오고 있다. 여기에서 우리는 버퍼 occupancy의 값이 비트율 왜곡의 측정치에서 Lagrange multiplier 형식으로 통합되는 것을 제안한다. 여기서 제안하는 알고리즘이 Viterbi 알고리즘과는 반대로 최적치에는 약간 못미치는 성능을 보여주지만, 대신 계산의 복잡도가 매우 낮을뿐 아니라, 버퍼 제어 알고리즘의 안정도를 Liapnov의 안정화이론을 이용해서 간단하게 설명 할 수 있다는 것이다.

Key words: 버퍼제어 적응양자화 라그랑지 승수법 버퍼 상태 점유

1. Introduction

A buffer-constrained adaptive quantization problem for image compression is considered. Some researchers[1,2] addressed an optimal control of buffer state within source coding frame and recently a formal description of the buffer control algorithm has been developed in a rate-distortion sense[3]. We propose a buffer control algorithm using a rate-distortion measure of the signal source as was done in [3]. But a different control law was applied to the feedback loop of the buffer state. Although the proposed algorithm does not provide the optimal performance, it can be implemented much easier than the optimal case's and its computational complexity is comparatively low to others[e.g. 3]. In addition the stability of this buffer control algorithm has been described briefly using Liapunov stability theory.

2. Buffer Control Algorithm

For given coding bit budgets, one tries to get high quality image transmission by minimizing

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distortion associated with image by buffering and using multiple quantizers. Distortion and rate of an information source sequence $\{x(t)\}_{t=1}^{n}$ are denoted by $D(x)=\sum_{t=1}^{n} e(x(t))$ and $R(x)=\sum_{t=1}^{n} r(x(t))$, respectively, where $\{e(x(t)),\ r(x(t))\}$ is set of points in Distortion-Rate curve which is determined by given budget and minimization algorithm of distortion sum measure. From rate-distortion theory, we know that rate $r(t)$ depends on distortion $e(t)$. In practice, the distortion is determined by selected quantizer and the rate is determined by the entropy coder. For instances, if we take a finer quantizer, the values of $e(t)$ and $r(t)$ get smaller and larger, respectively. On the other hand, if a coarser quantizer is used, the values of $e(t)$ and $r(t)$ are larger and smaller, respectively.

We now consider an optimal buffer control problem[3] as belows:

$$\min_{r(t)} \{\sum_{t=0}^{t} e(t)\}$$
$$\text{subject to } 0 \le B(t) \le B_{max}, \quad (1)$$
$$\text{for all } t=1,2,3,\cdots,n$$

with the buffer update

$$B(t) = B(t-1) + r(t) - \gamma, \quad (2)$$

where γ is the transmission rate of buffered content and the initial state of buffer is $B(0) = B_{init}$. It is assumed in this formulation that there is an explicit relationship between distortion $e(t)$ and rate $r(t)$ and thus we can always find a quantizer which provides the pair $\{e(t), r(t)\}$ which satisfies this explicit relationship. As described in [3], this formulation can be solved using dynamic programming, however, the computational complexity increases exponentially with t. Thus it can't be used in practice. We propose a practical solution to buffer state control with much less computational complexity.

A. Controlled Lagrange Multiplier Method

The optimal buffer control algorithm via dynamic programming approach can not be used in practice because of its computational burden. To overcome this difficulty, fast algorithm based on the optimal bit allocation method was proposed by Ortega *et al.* [3]. Here we propose an alternative method of buffer control by a direct feedback control of the buffer occupancy state using the controlled Lagrange multiplier method. Let us define a combined cost function:

$$T_{\lambda}(x(t)) = e(t) + \lambda(t) r(t) \quad (3)$$

For a given value of $\lambda(t)$, we can choose $r(t)$ and $e(t)$ that minimize $T_{\lambda}(x(t))$. The λ value controls the slope of Distortion-Rate (DR) curve. In other words, if buffer becomes full, the value of λ becomes large and it renders a small value of rate $r(t)$. Thus by incorporating the state of buffer occupancy to the value of λ in the combined cost function, we can obtain a buffer control algorithm which is called "controlled Lagrange multiplier (CLM) method" as follows:

$$\min_{r(t)} \{e(t) + \lambda(t) r(t)\}, \quad (4)$$

where

$$\lambda(t) = f(B(t)) = cB(t-1),\ c > 0, \quad (5)$$

where $f(\cdot)$ is non-decreasing function and $B(t)$ is given by (2). This is illustrated using Fig. 1 which shows dynamic determination of operational RD

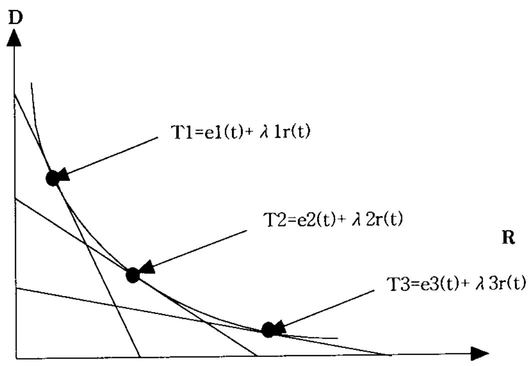

Fig. 1. Dynamic determination of operational RD points by adjusting the parameter λ based on the current buffer occupancy state $B(t)$

points by adjusting the parameter $\lambda(t)$ depending on the previous buffer occupancy state. The CLM method dynamically finds the suboptimal path that minimizes a combined total cost $T_\lambda(x(t))$ for consecutive N subimage blocks by feeding back the buffer occupancy state into the λ updating rule as illustrated in Fig. 2.

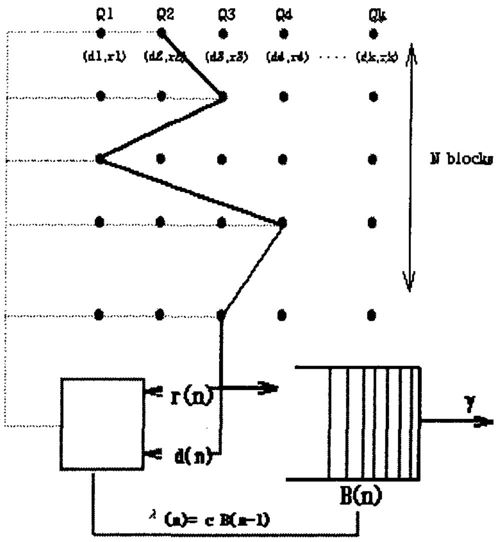

Fig. 2. Suboptimal path finding by minimization of a combined total cost T (e(t),r(t)) at consecutive N blocks.

B. Stability of the Algorithm

Suppose that the relationship between distortion and rate of information source is multiplicative in distortion. Then for given sequence of rate $\{r(t)\}_{t=1}^{n}$, the sequence of distortion is given by

$$e(t) = D(r(t)),\ t=1,2,\cdots,n$$

Then the rate which satisfies (4) is given []by

$$r(t)=g^{-1}(-\lambda(t))=g^{-1}(-f(B(t))\equiv h(B(t)), \quad (6)$$

where $g(\cdot)= dD/dR$ = the differential function of operational combined RD curve. The initial state of buffer and the desired equilibrium state of buffer are denoted by $B(0) = B_{init}$ and B^*, respectively. In general, the desired equilibrium state of buffer B^* is the half buffer size, i.e., $B^* = B_{\max/2}$. The details of derivation on the existence and determination of the equilibrium state of buffer and its stability is shown in [4]. We quote the stability results from [4] about buffer control algorithm obtained by Choi and Park as belows:

Theorem 5[4]: Buffer control algorithm which uses the primitive CLM method (i.e., $f(B(t)) = cB(t))$ has a unique equilibrium state of buffer B^* which is globally (asymptotically) stable, if average DR curve of information source $\{x(t)\}$ is an exponential DR curve and $B^* > 1/2 \cdot \ln\alpha,\ \alpha>1$

Proof: See Appendix D in [4].

3. Experimental Results

For experiments, an image source $x(t)$ of size 256x256 is divided into 8x8 subblocks which is JPEG coded by changing scale factor to obtain associated distortion and rate points for subblocks (see Fig. 3). The number of quantizers used in the experiment is five.

In simulations, the three methods are applied to the same sequence of image subblocks and results are summarized in Table 1-3 and Fig. 4-5. In Table 1, the total rates and performance indecies of the sequence of image block for each method are given. The performance index is defined by

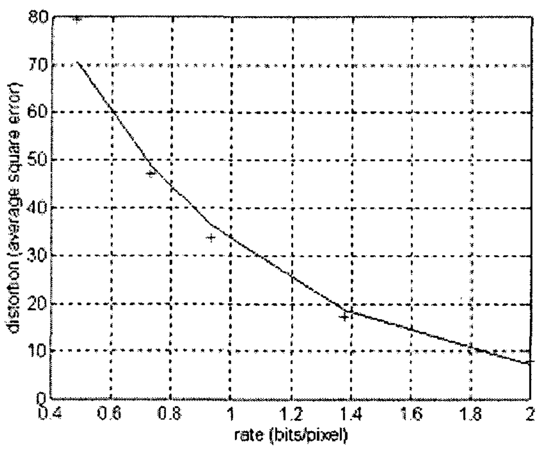

Fig. 3. Average distortion and rate points for five pairs of quantizer and entropy coder and its EDR curve which is fitted from five (D,R) points.

Table 1. Performance index and total rate for various methods (Note: the overhead bits in the CLM and the optimal bit allocation methods are excluded)

buffer control method	CLM	optimal bit allocation	direct bit allocation
performance index S	1.0005	1.2677	1.0000
total rate (bits)	949.7	952.9	952.6

Table 2. Performance index and total rate for the CLM method with different numbers of merged blocks m for buffer control (Note: the overhead bits are excluded.)

number of merged blocks	m = 1	m = 4	m = 8	m = 16
performance index S	1.0005	0.9727	0.9517	0.9992
total rate (bits)	949.66	952.34	954.38	972.14

$$S = \frac{\text{the sum of distortions for each method}}{\text{the sum of distortions for the direct bit allocation method}}$$

As we would expect, the performance index for the optimal bit allocation method is larger than the others. To reduce the overhead occurring from switching a pair of quantizer and entropy coder in the CLM method, the same pair of quantizer and entropy coder can be used over successive *m* blocks. As we see in Table 2, the performance index is decreased as the number of merging blocks *m* increases. As shown in Fig. 4, the buffer

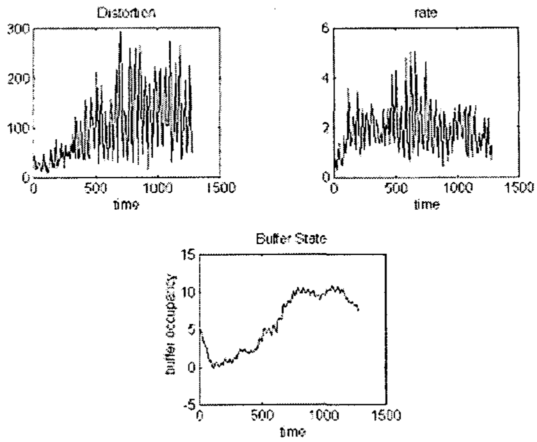

Fig. 4. The CLM buffer control method with the equilibrium state of buffer B=5 and r=0.9303(a) the sequence of distortions (b) the sequence of rates and (c) the state of buffer occupancy.

occupancy state is well controlled without causing any buffer underflow and/or overflow.

For second experiment, video bit streams were generated according to MPEG 2 MP@ML. Program sources for experiment are "Bicycle", "Flower Garden", "Football", and "Mobile & Calendar" consisting of 27 frames, respectively. Bit streams with 6 Mbps and 9 Mbps bitrate are generated with GOP size = 9 and frame distance between I picture and P picture = 3. Average bitrate R and distortion (mse) D were computed over 3 GOP blocks. Table 3 shows average bitrate and distortion for 3 GOP

Table 3. Average Rate(bps) and Distortion(mse) values for 3 GOP Blocks

MPEG 2 MP@ML N=9, M=3	GOP 1		GOP2		GOP3	
Sources	6Mbps (R,D)	9Mbps (R,D)	6Mbps (R,D)	9Mbps (R,D)	6Mbps (R,D)	9Mbps (R,D)
Source 1	(0.44, 62.02)	(0.67, 38.19)	(0.38, 83.72)	(0.57, 50.53)	(0.39, 80.64)	(0.58, 49.28)
Source 2	(0.43, 39.35)	(0.66, 23.05)	(0.38, 58.27)	(0.58, 34.55)	(0.39, 55.56)	(0.57, 33.37)
Source 3	(0.45, 27.18)	(0.67, 18.40)	(0.37, 37.43)	(0.57, 22.03)	(0.39, 36.78)	(0.59, 22.37)
Source 4	(0.43, 97.52)	(0.66, 61.87)	(0.37, 90.47)	(0.56, 56.69)	(0.39, 76.14)	(0.58, 47.23)

*source 1: Bicycle, source 2: Flower Garden, source 3: Football, source 4: Mobile&Calendar

blocks of program sources coded according to the aforementioned conditions.

An optimal composite rate and distortion is shown in Fig. 5 (a) and Fig. 5 (b) for each GOP (Group of Picture) block which was found out of 16 possible combinations by using the proposed buffer control algorithm. Fig. 5 (c) represents multiplexor buffer occupancy state evolving over time (i.e. GOP block). Initial buffer state can be set around the middle of total buffer capacity and here set to 6 Mbits. Length of video sequences used in the experiment is only 3 GOP blocks and may not be large enough to confirm a long-time behavior of the buffer state and examine image complexity(Please refer [3] as to the stability and long-term behavior of the proposed algorithm.). But we can see that the current buffer state which is input to mux buffer is regulated according to increase or decrease of the previous bitrate. Fig. 5 (d) represents all possible (R,D) points that can be produced for 3 GOP blocks.

In order to compare the performances of the proposed algorithm to that of the fixed rate encoder we define distortion performance index as $S_{GOP} = \frac{MSE_2}{MSE_1}$, where MSE_1 and MSE_2 represents mean square error computed by the proposed algorithm and the fixed rate algorithm, respectively.

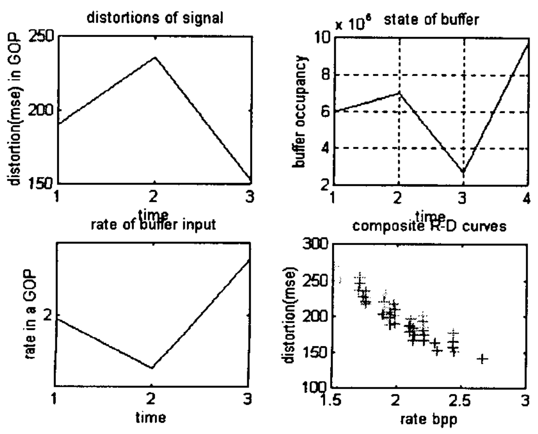

Fig. 5. Rate-distortion curve and the state of buffer occupancy.

When compared to the fixed rate (7.5 Mbps) encoder, performance index of the proposed method is 0.91, 0.93, and 0.89, respectively, for 3 GOP block. About 10 % less distortion for the fixed bitrate is obtained and implies that more information bits can be added if equal quality is permitted. In this paper we simply tested the possibilities of resources sharing for short GOP blocks by taking a global view of the problem of buffered rate and distortion control of MPEG 2 compressed video channels with hope of better video quality for DBS(Digital Broadcasting Satellite) applications

4. Concluding Remarks

A stable feedback control algorithm for a buffer-constrained adaptive quantization is proposed. The proposed buffer control algorithm demonstrated the stability of the buffer state occupancy under given buffer size and (exponential) average distortion-rate curve when it was applied to image and video. The very low computational complexity as opposed to the optimal method enabled fast approximation based on recursive feedback of the buffer state occupancy in the parameter λ.

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