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The Causation and Solution of Ringing Effect in DCT-based Video Coding

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Abstract**—**Ringing effect is one of the most annoying visual artifacts in digital video. It is a significant factor of subjective quality deterioration. However, there is a widely-accepted misunderstanding of its cause. In this paper, we propose a reasonable interpretation of the cause of ringing effect. Based on the interpretation, we suggest further two methods to reduce ringing effect in DCT-based video coding. The methods adaptively adjust quantizers according to video features. Our experiments proved that the methods could efficiently improve subjective quality with acceptable additional computing costs.

Keywords**—**ringing effect, video coding, subjective quality, DCT.

I. Introduction

Due to the great advancements of digital video compression techniques in the past ten years, digital video has already melted into our everyday lives omni-directionally. However, digital video has some exclusive artifacts never seen in analog video. Ringing effect is such a notorious artifact, which is often complained by videophiles but somehow overlooked by many experts and researchers.

Ringing effect means haloes and/or rings near sharp object edges in the picture. It is very well known in DVD fans. In fact, it is mentioned in almost every DVD review [1] recently. In many DVD movies, including both old movies and new movies, you can notice ringing effect every now and then. Fig. 1 shows an example picture picked from the "Thelma & Louise: Special Edition" DVD. Between the chine and the sky, there is a weird outer ring along the chine, which is so-called ringing effect. Ringing effect will become more obvious and annoying when viewed on big screen display devices, such as projectors.

Experts usually prefer objective quality to subjective quality for measurement. The measurement of objective quality needs "original" video [2]. However, the ultimate purpose of video is for human viewing. In most cases, audience cannot compare what they see with "original" video, since the "original" video is not available. They can only compare what they see with pictures in their experiences and memories. In these cases, subjective quality is as important as objective quality. If we achieve higher subjective quality with similar objective quality, both experts and mass audience will be satisfied.

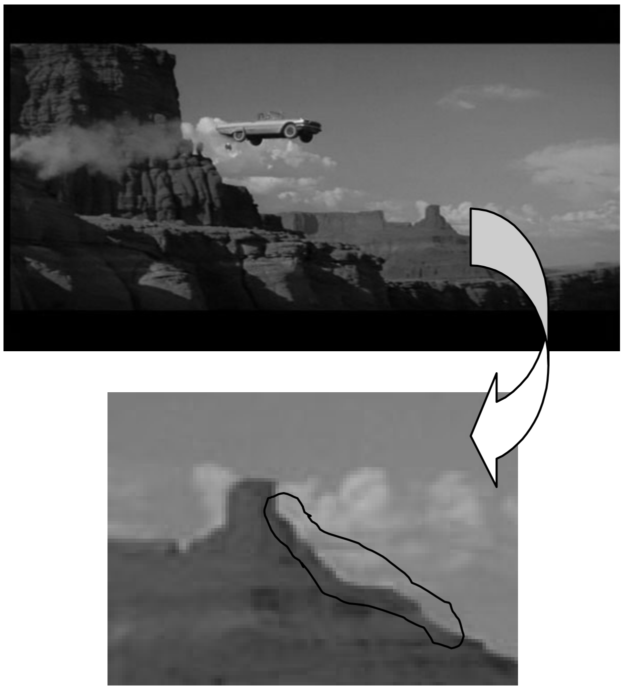

Figure I. Ringing effect example from DVD movie

If we use PSNR as the measure of objective quality, we will not find noticeable objective quality deterioration caused by ringing effect, since the haloes and rings only occupy very small areas. However, no one has ever seen such weird haloes and rings in real life, so ringing effect will be very noticeable in the pictures, i.e., will cause significant subjective quality deterioration. It is necessary to find a way to reduce ringing effect.

The rests of this paper are organized as follows. In section 2, we analyze the cause of ringing effect in detail. In section 3, we present two methods for ring effect reduction in DCT-based video coding. In section 4, we describe our experiments and results. Finally, in section 5, we discuss the usability of our method, and forecast its application foreground.

II. The Cause of Ringing Effect

In order to find a solution to address ringing effect, we should

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find its cause first. Since ringing effect is mainly reported and complained in DVD movies [1][3], it is natural to look for possible reasons in DVD production. There are so many stages in DVD production, such as, telecine (film digitalization), image pre-processing and restoration (for old movies only), compressing, and authoring. So the cause of ringing effect is not very apparent. Edge enhancement is a most widely accepted interpretation up to the present [1][3][4].

A. Enhancement-caused Ringing Effect

Many movies, especially old ones, go through digital pre-processes when they are transferred from films to digital high-definition masters in preparation for further stages. These pre-processes include digital noise reduction and edge enhancement [4]. The intended purpose of edge enhancement, which is similar to the "sharpen" filter in Adobe Photoshop, is improving contrast and clarity, since many old movies are blurry due to film aging and other damages. Fig. 2 shows the effect of edge enhancement.

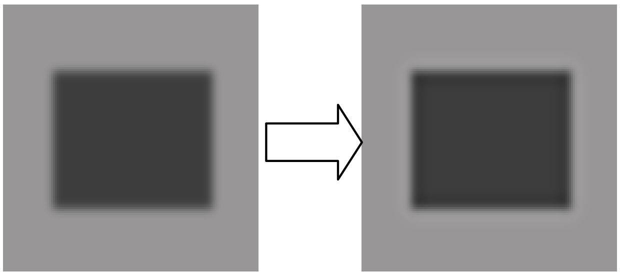

FIGURE II. THE EFFECT OF EDGE ENHANCEMENT

When overdone, edge enhancement will cause over chiseled look of objects in the picture. That is, the light side of the edge is much lighter than expected, and the dark side of the edge is much darker than expected. So it seems that objects have obvious haloes around their shapes. In Fig. 2, the halo around the black rectangle is difficult to notice. But, if the trend continues, the halo will be annoying eventually.

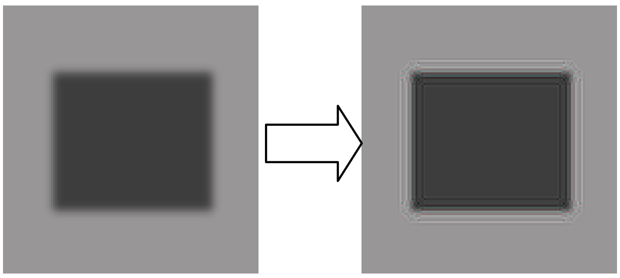

FIGURE III. THE OUTER RINGS CAUSED BY SOME SHARPEN ALGORITHMS

There are many edge enhancement algorithms, i.e. many sharpen algorithms. Some of them can cause not only one halo but also one or more "outer rings". That is, there are one or more dark rings in the light side of the edge, as well as one or more light rings in the dark side of the edge. It looks much worse than one halo only. Fig. 3 shows such a case generated by "Sharpen More" filter of Adobe Photoshop. However, not every sharpen algorithm can cause "outer rings". For example, you can apply "Sharpen Edges" filter of Adobe Photoshop on one picture as many times as you like, but you will never get "outer rings".

As analyzed above, edge enhancement assuredly can cause ringing effect. The enhancement-caused ringing effect happens in the pre-processing stage, which is before compressing. So one can think that compressing has nothing to do with ringing effect. This understanding is widely accepted. Many people, including most DVD fans in the web, regard edge enhancement as the only, at least the primary, cause of ringing effect.

However, the above understanding is a big misunderstanding. Some up-to-date DVD movies, which have never undergone edge enhancement during production, still have ring effect. For example, many consumers complained about "overdone edge enhancement" on the "Star Wars: Episode 2" DVD, but the authors declared that they did not apply any edge enhancement in the production [5]. On the other hand, though some sharpen algorithms can cause "outer rings", experienced video engineers can easily avoid such cases, because edge enhancement process is highly controllable. Our opinion is: numerous ringing effects, especially most "outer rings", are caused by compression.

B. Compression-caused Ringing Effect

Over-compression will cause ringing effect. Let us consider DCT-based compression. At the encoder side, pixels in spatial domain are transformed into coefficients in frequency domain, and then go through quantization. At the decoder side, coefficients go through inverse quantization and inverse DCT to reconstruct pixels. Almost all losses occur in the quantization stage.

Because of less importance, high-frequency coefficients will be quantized more heavily than low-frequency coefficients [2][6]. However, the blocks containing sharp edges correspond to more high-frequency components than normal blocks. These blocks will undergo much heavier losses while quantization. At the decoder side, pixels in spatial domain can be regarded as sum of all frequency components. The sum of low frequency components will assume a "wave" look (a series of rings). These rings should be compensated with high frequency components. In the case of blocks containing sharp edges, high frequency components are over eliminated, so the rings will not get enough compensation and will appear perceptibly. That is the cause of ring effect. Fig. 4 shows a 1-D case, and Fig. 5 shows a 2-D case.

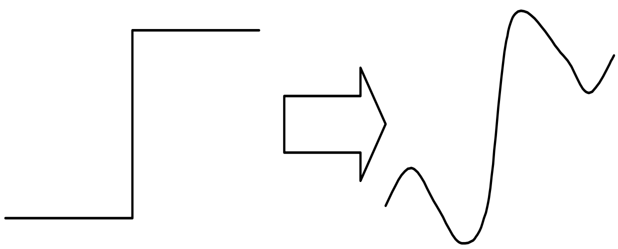

FIGURE IV. 1-D RINGING EFFECT CAUSED BY OVER-COMPRESSION

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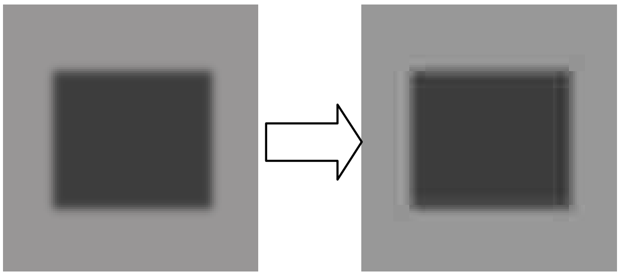

FIGURE V. 2-D RINGING EFFECT CAUSED BY OVER-COMPRESSION

It is not a new discovery that DCT-based compression can cause ringing effect. [7]-[9] observed the phenomena that one or more rings will appear near sharp edges in decoded pictures as long as the bitrate is not high enough. Actually, not only DCT but also other transform-based compression, such as wavelet-based compression [10][11], will generate such ringing effect. However, we think it is necessary to re-discuss compression-caused ringing effect, compare it with enhancement-caused ringing effect, and differentiate them.

C. Compare Enhancement-caused Ringing Effect with Compression-caused Ringing Effect

Edge enhancement is an intended process. Its essence is to strengthen high frequency components. When overdone, it will cause ringing effect.

Compression is also an intended process. Its essence is to weaken high frequency components. When overdone, it will also cause ringing effect.

Why both strengthening and weakening high frequency components will similarly cause ringing effect? In fact, compression-caused ringing effect is very different from enhancement-caused ringing effect, as follows:

1. Near the same original edge, the position and size of the enhancement-only caused ringing effect is different from compression-only caused ringing effect, as shown in Fig. 3 and Fig. 5.
2. Compression will often cause “outer rings”, as shown in Fig. 5. It’s a typical feature of overdone quantization. However, not every edge enhancement algorithm can cause “outer rings”.
3. Edge enhancement will always generate haloes. Actually, these haloes are expected results unless too noticeable. If not overdone, the haloes will make picture look vivid and crisp. Only overdone haloes will make audience uncomfortable. However, compression-caused haloes and outer rings are all unexpected byproducts. Only with high enough quantization precision, the intensities of haloes and outer rings will be low enough to inconspicuous.

Finally, why ringing effect is mainly noticed in DVD movies? On the one hand, other low-bitrate video applications averagely have much lower quality than DVD movies, so there are worse and more noticeable artifacts such as blocky effect in these low-bitrate applications. On the other hand, it implies that ringing effect is more difficult to reduce than other artifacts while bitrate increases.

III. REDUCING COMPRESSION-CAUSED RINGING EFFECT IN DCT-BASED VIDEO CODING

Compared with the whole picture, compression-caused ringing effect only occupies a small number of pixels, so that its influence on objective quality (measured with PSNR) is very low. But it will heavily deteriorate subjective quality, as discussed in Section 1. When audience notice it, they will feel uncomfortable because it deviates from their experiences in real life. So, developing some methods to reduce compression-caused ringing effect is reasonable and necessary.

Reference [7]-[9] noticed this necessity and suggested some methods to address it. Those methods involve some post-processing steps to reduce ringing effect after decoding. However, in many application areas, simpler decoder is better. For example, video industry usually does not care about the complexity and computing costs of encoders, because encoding step is located in the production process. Once a master disc is produced, they can manufacture as many retail discs as they want. So the production process is not very time-critical, and the encoding need not be real-time. On the other hand, more complexity and computing costs of decoders bring higher prices and lower popularization of end-user playback devices. So we think that it is perhaps more significant to do ringing effect reduction in encoders than in decoders.

Since compression-caused ringing effect is from overdone quantization, increasing quantization precision is a straight solution. With limited or appointed average bitrate, it is impossible and unnecessary to increase quantization precision of all blocks and all pictures. We present two ring effect reduction methods as follows. Both methods keep average bitrate and average PSNR unchanged, and improve subjective quality effectively.

A. Macroblock-based Ringing Effect Reduction

If video coding standards support macroblock-based quantiser adjustment, we can use macroblock-based ringing effect reduction. For example, in MPEG-2, every macroblock can contain a *quantiser_scale_code* field [6], so we can appoint different quantiser-scales for different macroblocks, as depicted in Fig. 6. We present macroblock-based ringing effect reduction method as follows:

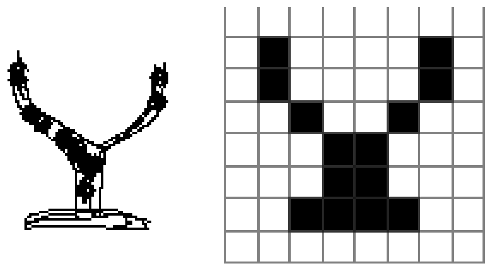

FIGURE VI. MACROBLOCK-BASED RINGING EFFECT REDUCTION

1. At the beginning of encoding a new picture, save the

original appointed quantiser-scales of all macroblocks in an array *q_scale_ori*[], where "original" means as if we didn't modify the encoding process, so we can still use any rate-control algorithms [12][13], such as 2-pass VBR, in advance. Quantiser scale of macroblock i is saved in *q_scale_ori*[i];

2. Analyze the picture, and find out which macroblocks contain "sharp" edges. We can do edge detection in either spatial domain or frequency domain (DCT coefficients can be utilized directly). Save the relative "sharpness" factors in an array *sharpness*[]. Sharpness factor of macroblock i is saved in *sharpness*[i]. If we do edge detection in frequency domain, sharpness factor can be calculated by absolute sum of products of every frequency and its coefficient;
3. Calculate the final quantiser_scales according to *sharpness*[]. The calculation as follows:
   q_scale_new[i] = *q_scale_ori*[i] + *Delta*(*sharpness*[i])
   We can choose one of the following *Delta* forms:
   $Delta(x) = f(x)$ where f is a one-to-one mapping function derived from experiments.
   or
   $$Delta\ (x) = \begin{cases} -a & \text{if } x \geq threshold \\ b & \text{if } x < threshold \end{cases}$$
4. We should also make the bit amount of the encoded picture as close as possible to the bit amount when quantized with the original appointed quantiser_scales. So, if the current average bitrate or instant bitrate becomes far enough from limits, we should ignore *q_scale_new*[] and do compensatory rate-control described in [12];
5. Quantization.

B. Picture-based Ringing Effect Reduction

If video coding standards do not support macroblock-based quantiser adjustment, we can only do picture-based ringing effect reduction. We can appoint different quantiser_scales for different pictures. We present picture-based ringing effect reduction method as follows:

1. Analyze the k^{th} picture; find out how many macroblocks contain sharp edges, where "sharp" means its sharpness exceeds certain threshold. The number of such macroblocks is saved in *sharp_mb_num*[k];
2. If $k > 0$, calculate the average from *sharp_mb_num*[0] to *sharp_mb_num*[k-1], and save the result as *average_sharp_mb_num*;
   If $k = 0$, let *average_sharp_mb_num* equal to *sharp_mb_num*[0];
3. Use *sharp_mb_num*[k] and *average_sharp_mb_num* as two additional factors to decide the quantiser-scale of this picture. In other words, we introduce the two additional factors into the original rate-control algorithm [12];
4. Quantization.

C. Comparison and Discussion

Macroblock-based ringing effect reduction is easy to implement, and convenient to control the bitrate. These advantages are disadvantages of picture-based ringing effect reduction.

There are several predefined parameters in both methods, such as a, b and threshold in macroblock-based ringing effect reduction, and threshold in picture-based ringing effect reduction. However, it is impossible to find an optimal parameter set that fits all video sequences. We can imagine that the optimal way is to determine the parameter set dynamically and adaptively. This could be further research works. Till now, we still use some tentative parameters derived from experiments.

Since edge detection is very simple to today's computers, additional computing costs introduced by both methods are acceptable.

Both methods need not change any bitstream grammar and syntax of existing video coding standards. They output standard bitstreams, which can be decoded by any compatible decoders. So, the methods can easily be implemented in any DCT-based video codecs, such as MPEG-1, MPEG-2, MPEG-4, and H.264. It's noteworthy that the methods only support VBR encoding, so decoders must be able to deal with VBR bitstreams. Considering that most present-day DVD movies are VBR encoded, the "VBR-only" disadvantage of the methods is very minor.

IV. Experiments

Two different codec platforms were adopted to test our methods. We implemented macroblock-based ringing effect reduction on MPEG-2 codec, and picture-based ringing effect reduction on H.264 codec.

A. Subjective Quality Evaluation

As discussed before, the only purpose of ringing effect reduction is to improve subjective quality under nearly same objective quality. So our evaluations were mainly subjective evaluations. These subjective evaluations complied with Recommendation ITU-R BT.500-11 [14], and were even more strict as described below:

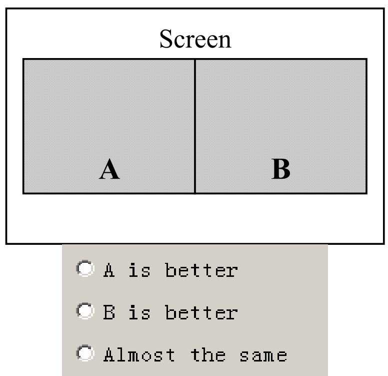

Figure VII. A/B Compare in Subjective Quality Evaluation

1. In each compare, two decoded video sequences, which came from one test video sequence, were displayed synchronously on the screen, as shown in Fig. 7. One was

encoded/decoded by our modified codec, the other was encoded/decoded by the original codec;

2. Audiences did not know which decoded video sequence was from our modified codec, and were not told what features should be noticed especially. They simply compared the two decoded video sequences based on their own perceptions;
3. After each compare, the on-screen locations corresponding to the original codec and our modified codec would be random exchanged (our evaluation system would record whether they were exchanged) to avoid possible influences on the perceptions caused by spatial location differences;
4. After the first pass of all the test video sequences, we exchanged the two on-screen locations of each compare according to the records of the first pass, and began the second pass;
5. Finally, for each test video sequence evaluated by each audience, we combined the results of two passes to one result. The combination rule is shown in Table 1.

TABLE I
THE COMBINATION RULE OF THE TWO PASSES

First Result	Second Result	Combined Result
A is better	A is better	Almost the same
A is better	Almost the same	The 1st A is better
A is better	B is better	The 1st A is better
Almost the same	A is better	The 1st B is better
Almost the same	Almost the same	Almost the same
Almost the same	B is better	The 1st A is better
B is better	A is better	The 1st B is better
B is better	Almost the same	The 1st B is better
B is better	B is better	Almost the same

Our audiences consisted of 20 laypeople, whose majors had nothing to do with video technology. Should subjective evaluation be taken by laypeople or professionals is a controversial problem. But in recent years, more researchers prefer laypeople. As we know, laypeople constitute the main part of the end users in most cases.

B. Macroblock-based Ringing Effect Reduction on MPEG-2 Codec

We used 10 standard test video sequences and 10 movie sequences extracted from DVD movies as our test data sets. The resolutions of all the video sequences were 720×480. The original codec and our modified codec were set to generate the same average bitrates. The average PSNR of bitstreams generated by the original codec and our modified codec were also almost the same. So the differences were on the subjective quality.

Different video sequences gave different results. Those more sharp and vivid video sequences gave better results. The average results of 20 video sequences are shown in Table 2.

TABLE II
SUBJECTIVE EVALUATION RESULTS OF MACROBLOCK-BASED RINGING EFFECT REDUCTION ON MPEG-2 CODEC

Average bitrate (Mbps)	Original is Better (votes)	Almost the Same (votes)	Modified is Better (votes)
3.0	0	0	20
4.0	0	1	19
5.0	1	3	16
6.0	3	8	9
7.0	4	13	3

The results proved that ringing effect would be more inconspicuous when average bitrate turned higher.

C. Picture-based Ringing Effect Reduction on H.264 Codec

We used 10 standard test video sequences and 10 movie sequences extracted and down-sampled from DVD movies as our test data sets. The resolutions of all the video sequences were 352×240. The original codec and our modified codec were set to generate the same average bitrates. The average PSNR of bitstreams generated by the original codec and our modified codec were also almost the same. So the differences were on the subjective quality.

Similarly, different video sequences gave different results, and more sharp video sequences gave better results. The average results of 20 video sequences are shown in Table 3:

TABLE III
SUBJECTIVE EVALUATION RESULTS OF PICTURE-BASED RINGING EFFECT REDUCTION ON H.264 CODEC

Average bitrate (Kbps)	Original is Better (votes)	Almost the Same (votes)	Modified is Better (votes)
200	2	2	16
300	3	2	15
400	2	5	13
500	4	9	7
600	3	13	4

The results also proved that ringing effect would be more inconspicuous when average bitrate turned higher.

Table 2 shows better results than Table 3. It is because the macroblock-based method is more efficient than the picture-based method.

V. CONCLUSION

Ringing effect is a notorious artifact in digital video. We discussed its appearance, its significant influence on video subjective quality, and its cause.

We presented two methods to improve subjective quality in DCT-based video compression by reducing compression-caused ringing effect. One is macroblock-based ringing effect reduction; the other is picture-based ringing effect reduction. Macroblock-based ringing effect reduction method is applicable only on macroblock-level quantiser adjustable video coding standards. Picture-based ringing effect reduction method is applicable on picture-level quantiser adjustable video coding standards.

Subjective evaluation results of experiments proved that our methods are valuable and viable.

Our methods have three advantages: easy to implement; acceptable computing costs; standard output bitstreams. So any video compression application, which is VBR-supported and not very time-critical, can benefit from our methods. At least, our methods can be directly used to improve the subjective quality of DVD movies.

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