AN APPROACH FOR ENABLING DCT/IDCT ENERGY REDUCTION SCALABILITY IN MPEG-2 VIDEO CODECS

R. Henning and C. Chakrabarti
Department of Electrical Engineering
Arizona State University
Tempe, Arizona 85287-5706

ABSTRACT

It would be desirable, in terms of energy conservation, to use a low complexity approximate algorithm to do all DCT and IDCT computation in an MPEG-2 video codec. However, there is a significant quality penalty associated with this approach that may not always be acceptable. A practical algorithmic method is studied here for achieving scalable energy reduction during DCT and IDCT computation in MPEG-2 video codecs at the expense of reasonable amounts of quality. For example, by applying exact and approximate DCT/IDCT algorithms appropriately, the energy consumption of DCT and IDCT execution in two video codecs communicating with one another can be reduced by 8% for quality reduction of 0.4 dB average PSNR, 14% for 0.8 dB reduction, or 22% for 1.4 dB reduction.

1. INTRODUCTION

Energy scalability, similar to bitrate scalability, trades quality for a corresponding level of energy consumption, allowing an application to be dynamically configured according to system needs. Emerging wireless video applications could benefit from an energy scalable video codec, because compressing and decompressing video costs significant energy, yet a fixed energy design may not be the best solution. The level of energy reduction needed and quality degradation that is acceptable can depend on variables such as the user, the video content, and the state of the power supply. The Discrete Cosine Transform (DCT) and its inverse, the IDCT, can consume a large percentage of the energy in an MPEG video codec, making them important targets for enabling energy scalability.

Dynamically varying an implementation based on nonstationary data characteristics so that the energy consumption is reduced has been studied in [1, 2]. For example, Goel and Shanbhag showed that the energy consumption of a particular Reed-Solomon codec implementation can be reduced by 55% on average by powering down taps that are not required to meet a desired bit error rate for an input with dynamically varying SNR. Lengwehasatit and Ortega have considered tradeoffs between quality and speed for DCT approximations [3], but not energy consumption. They showed significant speed gains, around 25%, in software JPEG encoding by choosing from a variety of approximations, depending on the quantization resolution used for each 8X8 block.

In this paper, a practical algorithmic approach is studied for achieving scalable energy reduction during DCT and IDCT computation in MPEG-2 video codecs. Both exact and approximate DCT/IDCT algorithms are executed according to frame type in various ways to achieve different amounts of quality/energy tradeoff. The best configurations for achieving energy reduction scalability with these methods are presented for three practical applications. These include one-way video communication where only decoder energy consumption is of concern, one-way video communication where only encoder energy consumption is of concern, and two-way video communication where energy consumption is a concern in both communicating devices. Key experimental results that led to selection of some of the configurations, like the importance of matching encoder IDCT and decoder IDCT methods and preserving I frame quality, are also discussed.

2. ENERGY SCALABILITY APPROACH

Our approach to trading off DCT/IDCT quality for energy consumption in MPEG-2 video codecs involves mixing execution of exact and low energy approximate algorithms in a data-dependent manner. It would be most desirable, in terms of energy conservation, to use a low complexity, approximate algorithm to do all DCT/IDCT computation in an MPEG-2 codec. However, there is a significant quality penalty associated with this that may not always be acceptable. By allowing both exact and approximate DCT/IDCT algorithms to be applied, an improved quality/energy tradeoff can be achieved. In addition, multiple configurations can be supported that tradeoff different amounts of quality and energy.

One exact and one approximate 8 point 1-D DCT/IDCT algorithm in particular have been chosen to study the effectiveness of this approach. These 1-D DCT/IDCT algorithms are applied to the codec using the Row-Column 2-D DCT/IDCT. The exact DCT/IDCT algorithm chosen requires only 5 multiplications and 29 additions [4]. We call this method the Scaled Exact (SE) 1-D DCT/IDCT algorithm, because outputs of the DCT algorithm and inputs to the IDCT algorithm are scaled. To compute a 1-D DCT/IDCT with fewer than 5 multiplications, approximations can be employed. The approximation chosen for this paper was introduced in our previous work [5]. It is an 8 point 1-D DCT/IDCT approximation that uses no multiplications and only 28 additions. This algorithm, referred to as Scaled Approximate (SA) in this paper, is an approximation of the exact

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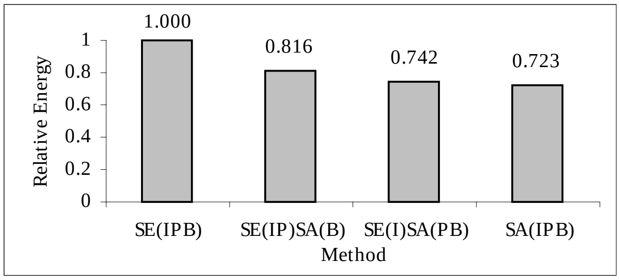

Figure 1. Relative energy estimates of mixing methods for either the encoder DCT or a decoder IDCT.

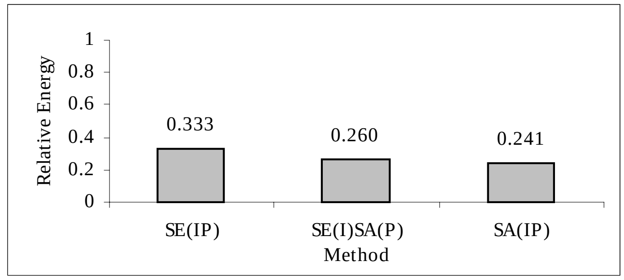

Figure 2. Relative energy estimates of mixing methods for the encoder IDCT.

1-D DCT/IDCT algorithm in [6]. Similar approximations can be found in [3].

Two methods of mixing execution of the exact and approximate algorithms to increase quality while enjoying the energy conservation benefits of the approximate algorithm are proposed here for encoder DCTs and decoder IDCTs. The first is to use the SE algorithm for I and P frames of a group of pictures (GOP) and the SA algorithm for B frames. This method is based on two characteristics of a B frame. First, unlike I and P frames, B frames are not referenced when inter frame coding is applied to macroblocks in P and B frames. Thus, when this method is applied to decoder IDCTs, quality reduction associated with approximate processing is confined to B frames, rather than spread to other frames in the GOP. When this method is applied to encoder DCTs, I and P frame quality is affected by rate control only because B frame coding efficiency is lost.

The second characteristic of a B frame is that more macroblocks of B frames tend to be inter frame coded than P frames. Only the residual portion of such a macroblock is distorted by SA DCT computation in the encoder or SA IDCT computation in the decoder. Therefore, these macroblocks tend to be more robust to associated quality degradation. In a typical GOP, like one of the form IBBPBBPBBPBBPBB, this method allows the lower energy SA algorithm to be used for 2/3 of the frames in a sequence, while the SE algorithm is used for only 1/3.

The second mixing method that can be applied to either encoder DCTs or decoder IDCTs uses the SE algorithm only for the I frames, while the SA algorithm is used for P and B frames. This method is based on characteristics of I and P frames. Since an I frame can be the basis for inter frame coding throughout a GOP, its integrity is in the greatest need of preservation. Additionally, unlike an I frame, a significant number of macroblocks of a P frame tend to be inter frame coded, though less than in a B frame. As was the case for B frames, these macroblocks tend to be more robust to approximation than intra coded macroblocks. In this method, the SA algorithm is used for 14/15 of the frames in the example GOP and the SE algorithm is used for only 1/15. Other methods, like only approximating subsets of P and/or B frames in a GOP are also possible, but many important aspects of such methods can be studied with the two presented here.

As for the encoder IDCT, only one mixing method is considered here: IDCTs applied to I frames are computed with the SE algorithm, while IDCTs applied to P frames are computed with the SA algorithm. (Only I and P frames are processed with encoder IDCTs.) By approximating the encoder IDCT, coding efficiency of macroblocks that use the affected reference frame in the encoder will be decreased. Quality may be further impacted if the same approximation is not used for the same frame in the decoder, because encoder and decoder reference frames for inter frame coding will not match. With this method, the SA algorithm is used for 4/5 of I and P frames in the example GOP, while the SE algorithm is used for 1/5.

3. ENERGY COMPARISONS

Differences in the number and type of operations performed by each of the DCT/IDCT computation methods described in the previous section can lead to significant energy consumption differences when implemented. The greatest benefit occurs when these methods are implemented in hardware rather than software, since software typically requires overhead that dwarfs data-path operation energy.

To compare the different methods, we consider the energy consumption of multipliers, adders, transposition memory, and control logic. Binary shifts used to avoid overflows and implement shift-and-add multiplications are assumed to be hard wired, so they have little effect on overall energy consumption. The SE and SA algorithms were found to produce quality near that of double precision versions of each algorithm with 16 bit integer multipliers, 16 bit integer adders, and a 64 word SRAM using 16 bit words. Relative energy per operation estimates for multiplication, addition, and memory accesses can be found by assigning a certain functional unit (a 16 bit addition in this case) a normalized energy per operation value of 1. The other operations are then assigned energy per operation values relative to the 16 bit addition. Here, we choose to assign a relative energy value of 3.600 to a 16 bit multiplication, 0.652 to an SRAM read, and 1.333 to an SRAM write. These values are based on general relationships published in [7] but reflect scaling of energy with respect to memory size.

To obtain energy estimates for the DCT/IDCT methods, a 15 frame GOP of the form IBBPBBPBBPBBPBB was assumed. The estimates have been normalized by the energy of the case where only the SE algorithm is used for the encoder DCT or decoder IDCT for the entire GOP. This case consumes the most energy of all methods considered. The control energy estimate used is 20% of this highest energy case and remains constant for all methods, except for the encoder IDCT where it is 1/3 of this value.

Figure 1 shows the relative energy consumption of either the encoder DCT or decoder IDCT, since both consume the same amount of power for the same method. Figure 2 shows the relative energy consumption of the encoder IDCT. The notation used in these figures indicates which frame type uses which

Enc DCT	Enc IDCT	Dec IDCT	Qual	Red	Ener	% Red
SE(IPB)	SE(IP)	SE(IPB)	32.93	0.00	1.00	0.0%
SE(IPB)	SE(IP)	SE(IP)SA(B)	32.67	0.26	0.82	18.4%
SE(IPB)	SE(I)SA(P)	SE(I)SA(PB)	32.14	0.78	0.74	25.8%

Table 1. Quality/energy tradeoff of best configurations when concerned with decoder energy only.

algorithm. For example, SE(IP)SA(B) indicates that I and P frame DCTs (or IDCTs) are computed with the SE algorithm, while B frames employ the SA algorithm for DCT (or IDCT) computation. Note that encoder IDCTs apply only to I and P frames, since B frames are not referenced in inter frame coding.

4. EXPERIMENTAL RESULTS

To distinguish the proposed DCT and IDCT computation methods in terms of the tradeoff between quality and reduced energy consumption, the needs of the specific application must be considered. Applications include one-way and two-way video communication where the energy reduction and video quality needs of the communicating devices may be different. To study the most practical of these situations, experiments were run using the MSSG MPEG-2 video codec. Four standard video sequences were considered, Flower Garden, Football, Mobile, and Table Tennis. Each sequence has a frame resolution of 352X240 pixels, color subsampling of 4:2:0, and frame rate of 30 frames per second. This resolution was chosen because it is expected that the primary applications of this technique would be in hand-held devices capable of relatively good quality. Each sequence was encoded with a 15 frame GOP structure of the form IBBPBBPBBPBBPBB. Based on our previous work with IDCT approximations [5], a fixed bitrate of 4 Mbps (using the rate control technique included in the MSSG codec) was employed for encoding to best demonstrate the capabilities of these techniques. Quantitative quality results were obtained in terms of PSNR measurements. The authors made subjective visual observations of quality and verified that they closely follow the quantitative results.

Given the methods in Figures 1 and 2, there are 48 different ways in which the encoder DCT, encoder IDCT, and decoder IDCT can be configured for one-way video communication. However, only the few best alternatives need be identified for a particular application in order to provide a useful variety of quality/energy tradeoff options. The best configurations identified through experimentation for three communication situations will be discussed next. An example of the notation that will be used to describe a particular system configuration for one-way communication is SE(I)SA(PB)/SE(IP)/SE(IP)SA(B). This notation means that SE(I)SA(PB) is used for the encoder DCT, SE(IP) is used for the encoder IDCT, and SE(IP)SA(B) is used for the decoder IDCT in the communication path.

First, consider a one-way communication situation where decoder energy reduction scalability is needed, while encoder energy consumption is not a concern. An example of an application with these characteristics is a wireless internet appliance that receives streaming video from a tethered server. The configurations shown in Table 1 are the best quality/energy tradeoffs available in this case from the original 48. Also included in this table are the average PSNR for the luminance component of the output when the Flower Garden sequence is encoded and decoded, the associated reduction in average PSNR with respect to the SE(IPB)/SE(IP)/SE(IPB) configuration, the relative energy consumption estimates for the decoder IDCTs, and the associated percentage reduction in energy with respect to the SE(IPB)/SE(IP)/SE(IPB) configuration. With these configurations, a small amount of video quality, 0.26 dB average PSNR for the Flower Garden sequence, can be traded for an 18.4% reduction in energy consumption during IDCT computation in the decoder. For an additional 0.53 dB reduction, 25.8% energy reduction can be achieved.

Unlike our previous study of this situation in [5], in this paper we assume it is possible to change the encoder configuration to best suit the selected decoder IDCT method. For example, it would cost 1.64 dB in total average PSNR reduction, rather than 0.78 dB, if the encoder IDCT method used was SE(IP) instead of SE(I)SA(P) in the last configuration of Table 1. Thus, it is indeed important to allow the IDCT in the encoder to be changed, assuming it is possible to notify the encoder which decoder method will be used. The reason that the SE(I)SA(P) encoder IDCT produces the best results when the SE(I)SA(PB) decoder IDCT is employed is that reference macroblocks used for inter frame coding are calculated using the same IDCT methods in the encoder and decoder. If the SE(IP) encoder IDCT is instead coupled with the SE(I)SA(PB) decoder IDCT, reference macroblocks formed from P frames will be calculated with the SE IDCT in the encoder and the SA IDCT in the decoder. The resulting difference between these reference macroblocks contributes directly to error in corresponding reconstructed macroblocks at the decoder. Such error causes even more problems when the reconstructed macroblock is part of a P frame, because the error will be propagated into other frames that reference this macroblock.

Another important result revealed by analysis of the possible configurations is that at first glance it appears that energy reduction of 27.7% can be achieved for the decoder IDCT at the expense of a relatively small total average PSNR reduction of 1.06 dB with the SE(IPB)/SA(IP)/SA(IPB) configuration. Such a result hints that the difference in quality between this method and SE(IPB)/SE(I)SA(P)/SE(I)SA(PB) might be negligible and allow a small amount of additional energy reduction. However, in this case, using the average PSNR quality measure is deceiving. If the PSNR for each frame of the sequence is considered instead as is shown in Figure 3, a potentially serious problem can be identified.

In Figure 3, it can be seen that all of these configurations have very similar quality for P frames and B frames. However, there is a sharp divergence in quality for I frames. SE(IPB)/SA(IP)/SA(IPB) and SA(IPB)/SE(IP)/SE(IPB) continue to have almost identical quality, whereas the other two configurations, achieve 1 to 3 dB better quality for I frames. Though SE(I)SA(PB)/SE(IP)/SE(IPB) can itself have I frame quality around 1 dB less than SE(IPB)/SE(I)SA(P)/SE(I)SA(PB), this is not that serious. In this case, the B frames that precede and follow an I frame have nearly the same level of quality as the I frame, so it is difficult to perceive I frame degradation while viewing the video. The same is not true for the SE(IPB)/SA(IP)/SA(IPB) and SA(IPB)/SE(IP)/SE(IPB) configurations, where this artifact can potentially be seen by the viewer as momentary lapses in quality whenever I frames appear. Thus, algorithms that use SA(I)SE(PB) in place of SA(IPB) in the encoder or decoder can be better alternatives in terms of quality, while costing only a small amount of additional energy.

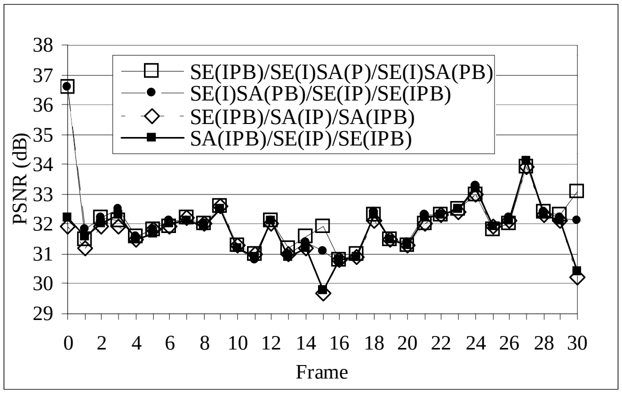

Figure 3. Frame-by-frame quality comparison between configurations that use SA(IPB) and those that use SE(I)SA(PB).

Now, consider a one-way video communication system where decoder energy reduction is not important and encoder energy reduction scalability is needed. An example of such an application is a wireless video camera that encodes video for later viewing on a device that is plugged in. For this case, the best quality/energy tradeoffs are shown in Table 2. With these techniques, a small amount of video quality, 0.37 dB average PSNR for the Flower Garden sequence, can be traded for a 13.8% reduction in energy consumption during DCT and IDCT computation in the encoder. For an additional 0.41 dB reduction, 19.4% energy reduction can be achieved. If energy consumption must be minimized, a rather large additional quality reduction of 1.10 dB can be traded for a total reduction of 24.9% energy reduction. This last option is somewhat interesting because it does not match the encoder IDCT with the decoder IDCT as discussed previously. It turns out that if decoder energy is not a concern, the best quality that can be achieved while using SE(I)SA(PB) for the encoder DCT and SE(I)SA(P) for the encoder IDCT is by using SE(IPB) for the decoder IDCT. This result occurs because the high quality of P and B frame decoding with the SE(IPB) IDCT in the decoder offsets errors due to reference macroblock mismatch that results when a P frame is referenced. A nice benefit of all these configurations is that they employ a decoder that uses no approximations. Thus, any standard MPEG-2 decoder can decode video from any of these encoder configurations and produce the expected quality.

Finally, let us consider an example involving two-way video communication. In this situation there are two communication channels and each communicating device contains an encoder and decoder from separate channels. Assume that energy reduction scalability is important in both devices of this system. An example of such an application is two wireless video appliances communicating with one another. The configurations shown in Table 3 are the best options available, assuming it is desired that the quality of both channels be the same. In this table, the configuration and quality, in terms of average PSNR, for one channel is shown, as well as the relative energy consumption for all DCT and IDCT computation in one device. This data is identical for both channels and both devices. With these techniques, a small amount of video quality, 0.37 dB average PSNR in both channels for the Flower Garden sequence, can be traded for a 7.9% reduction in energy consumption during DCT and IDCT computation in the encoder and decoder of both devices. For an additional 0.41 dB reduction, 14.2% energy reduction can be achieved. For an additional 0.66 dB reduction, 22.1% energy reduction can be achieved. Finally, for an additional 0.75 dB reduction, 25.3% energy reduction can be achieved. However, this may be too much quality to give up in both channels to reduce energy consumption by only 3.2% more.

Enc DCT	Enc IDCT	Dec IDCT	Qual	Red	Ener	% Red
SE(IPB)	SE(IP)	SE(IPB)	32.93	0.00	1.33	0.0%
SE(IP)SA(B)	SE(IP)	SE(IPB)	32.55	0.37	1.15	13.8%
SE(I)SA(PB)	SE(IP)	SE(IPB)	32.14	0.78	1.08	19.4%
SE(I)SA(PB)	SE(I)SA(P)	SE(IPB)	31.04	1.88	1.00	24.9%

Table 2. Quality/energy tradeoff of best configurations when concerned with encoder energy only.

Enc DCT	Enc IDCT	Dec IDCT	Qual	Red	Ener	% Red
SE(IPB)	SE(IP)	SE(IPB)	32.93	0.00	2.33	0.0%
SE(IP)SA(B)	SE(IP)	SE(IPB)	32.55	0.37	2.15	7.9%
SE(IPB)	SE(I)SA(P)	SE(I)SA(PB)	32.14	0.78	2.00	14.2%
SE(IP)SA(B)	SE(I)SA(P)	SE(I)SA(PB)	31.48	1.44	1.82	22.1%
SE(I)SA(PB)	SE(I)SA(P)	SE(I)SA(PB)	30.73	2.19	1.74	25.3%

Table 3. Quality/energy tradeoff of best configurations when concerned with energy of both communicating codecs.

5. CONCLUSIONS

The approach presented here shows the great potential data-dependent algorithm mixing techniques have for applications requiring energy reduction scalability or simply fixed energy reduction at the expense of a small amount of quality. Other DCT/IDCT approximations and algorithm mixing methods may provide better or wider ranging quality/energy tradeoffs for certain applications. Thus, they are good subjects for future work. By also designing other parts of an MPEG-2 codec to trade significant energy for small amounts of quality, a very effective energy scalable or fixed low energy codec could result.

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