Prediction of Zero Quantized DCT Coefficients in H.264/AVC Using Hadamard Transformed Information

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***Abstract*—This paper presents an efficient approach for detecting zero quantized discrete cosine transform (ZQDCT) coefficients using the sum of absolute transformed difference (SATD). Previously, all the ZQDCT prediction approaches employ the sum of absolute difference (SAD) available ahead of DCT and quantization (Q) for early detection. However, when the Hadamard transform is enabled for H.264/AVC encoding, only the SATD instead of SAD is available before DCT and Q, and all the prediction approaches can not be directly applied. To solve this problem, the Gaussian distribution is applied to study the integer 4×4 DCT coefficients in H.264/AVC and hence an adaptive scheme with multiple thresholds against SATD is derived to realize different types of DCT and Q implementations. In addition, another two SATD based sufficient conditions are proposed for early detecting zero quantized DC coefficients for the luma components encoded with the intra16 $\times$ 16 mode and the chroma components. The experimental results demonstrate that the proposed approach can greatly reduce the DCT and Q computations and obtain almost the same rate-distortion performance as the original encoder.**

***Index Terms*—Discrete cosine transform (DCT), Gaussian distribution, Hadamard transform, H.264/AVC, quantization (Q).**

I. Introduction

THE STATE-OF-THE-ART video coding standard H.264/AVC achieves significant gains in compression efficiency compared to previous standards. However, the coding complexity is tremendously increased. Therefore, there is a significant interest in reducing computations for H.264/AVC. In general, most of the computations of H.264/AVC are consumed in the mode decision stage where variable block size motion estimation (ME) is employed. Previously, the efforts are mainly focused on fast ME algorithms and fast mode selection algorithms. After the ME and mode selection are optimized, another attempt to further reduce the computations of H.264/AVC is to cut down the discrete cosine transform (DCT) and quantization (Q) computations by employing zero quantized DCT (ZQDCT) early detection approaches [1]–[3]. These ZQDCT early detection approaches employ sum of absolute difference (SAD) to derive the early detection condition for predicting ZQDCT coefficients before DCT and Q and thus reduce redundant DCT and Q computations.

However, when the Hadamard transform is enabled for H.264/AVC encoding, the early detection conditions provided in [1]–[3] can not be applied since only the sum of absolute transformed difference (SATD) instead of SAD is available after inter- or intra-prediction. To address this problem, we propose an efficient approach to early detecting ZQDCT coefficients by utilizing the SATD information when the Hadamard transform is enabled for H.264/AVC. All the three types of DCT and Q [4] in H.264/AVC are considered. Firstly, a Gaussian distribution based model is applied to study the integer DCT coefficients of the Normal4 $\times$ 4 type. As a result, four thresholds against SATD are derived to determine five kinds of DCT, Q, inverse quantization (IQ), and IDCT implementations: *Skip*, 1×1, 2×2, 3×3, and 4×4. In addition, we also study the LumaDC4 $\times$ 4 and ChromaDC2 $\times$ 2 types of DCT and Q, and provide SATD based sufficient conditions under which the DC coefficients of these two types are quantized to zeros. Experimental results demonstrate that the proposed approach is able to reduce 30%–40% of the total DCT and Q computations on average and obtains almost the same rate-distortion (R-D) performance as the original encoder. The rest of this paper is organized as follows. The preparations and related works are briefly presented in Section II. In Section III, the proposed SATD based ZQDCT prediction approach is discussed theoretically. Experimental results are shown in Section IV. Finally, Section V concludes this paper.

II. Preparations and Related Works

In this section, we first introduce three types of DCT and Q functions [4] employed in H.264/AVC. Then the SAD based ZQDCT early detection approach [3] is concisely reviewed, which is associated with the proposed SATD based early detection method.

A. Integer DCT and Quantization in H.264/AVC

1) Normal4 $\times$ 4 Type: For a 4×4 residual block $f(x,y)$, $0 \le x,y \le 3$, the integer transform is

$$F(u,v) = \sum_{x=0}^{3}\sum_{y=0}^{3} f(x,y) \cdot A(x,u) \cdot A(y,v) \tag{1}$$

where

$$A(m,n) = \left\langle \frac{2.5C(n)}{\sqrt{2}} \cos\frac{(2m+1)n\pi}{8} \right\rangle \tag{2}$$

$C(n) = 1/\sqrt{2}$, for $n = 0$; and $C(n) = 1$, otherwise. The operator $\langle x \rangle$ denotes to round the operand x to the nearest integer. Given a Q parameter Q_p, the quantized coefficient $Z(u,v)$, $0 \le u,v \le 3$, is written as

$$Z(u,v) = \mathrm{sign}(F(u,v)) \cdot (|F(u,v)| \cdot M(u,v) + c) \gg \mathrm{qbits} \tag{3}$$

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where $\mathrm{qbits} = 15 + \mathrm{floor}(Q_p/6)$, $\gg$ indicates the binary shift right, c is $\langle 2^{\mathrm{qbits}}/3\rangle$ for intra-blocks or $\langle 2^{\mathrm{qbits}}/6\rangle$ for inter-blocks, and $M(u,v)$ is the multiplication factor.

2) LumaDC4 × 4 Type: If a macroblock (MB) is encoded with the intra16 × 16 mode, each 4 × 4 residual block is first transformed using the Normal4 × 4 type described above. Then the DC coefficients of each 4 × 4 block are transformed again using a 4 × 4 Hadamard transform as

$$Y_4 = HF_4H^T/2 \tag{4}$$

where

$$H = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix} \tag{5}$$

F_4 is the block of 4 × 4 DC coefficients and Y_4 is the transformed block. Then quantized DC coefficients are obtained by

$$\begin{aligned} |Z_4(u,v)| &= (|Y_4(u,v)| \cdot M(0,0) + 2c) \\ &\quad \gg (\mathrm{qbits}+1) \\ \mathrm{sign}(Z_4(u,v)) &= \mathrm{sign}(Y_4(u,v)). \end{aligned} \tag{6}$$

3) ChromaDC2 × 2 Type: The 4 × 4 blocks of chroma components are first transformed using the Normal4 × 4 type. Then the DC coefficients of each 4 × 4 block of chroma coefficients are grouped in a 2 × 2 block F_2 and are further transformed using a 2 × 2 Hadamard transform as

$$Y_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} F_2 \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{7}$$

Q of the 2 × 2 output block Y_2 is performed by

$$\begin{aligned} |Z_2(u,v)| &= (|Y_2(u,v)| \cdot M(0,0) + 2c) \\ &\quad \gg (\mathrm{qbits}+1) \\ \mathrm{sign}(Z_2(u,v)) &= \mathrm{sign}(Y_2(u,v)). \end{aligned} \tag{8}$$

B. Related Works

In the following, a brief description of the approach [3] is given, i.e., how to utilize the Gaussian distribution and SAD for early detecting ZQDCT coefficients. This is useful to elicit the proposed SATD based early detection approach.

From (3), the sufficient condition for $F(u,v)$ to be quantized to zero in the Normal4 × 4 type can be given as

$$|F(u,v)| < T(u,v), \quad T(u,v) = \frac{2^{\mathrm{qbits}} - c}{M(u,v)}. \tag{9}$$

Suppose the residual pixel values $f(x,y)$ at the input of DCT are approximated by a Gaussian distribution with zero mean and variance σ^2 as

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}}, \quad -\infty < x < +\infty. \tag{10}$$

The expected value of $|x|$ can be calculated as

$$E[|x|] = \int_{-\infty}^{+\infty} |x| \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}} dx = \sqrt{\frac{2}{\pi}}\sigma. \tag{11}$$

Since $\mathrm{SAD} = \sum_{x=0}^{3}\sum_{y=0}^{3}|x|$, $E[|x|]$ can be approximated as $E[|x|] \approx \mathrm{SAD}/N$ where N is the number of coefficients (i.e., 16 for a 4 × 4 block). Hence, we can get

$$\sigma \approx \sqrt{\frac{\pi}{2}} \frac{\mathrm{SAD}}{N}. \tag{12}$$

Note that the variance of the (u,v)th DCT coefficient $\sigma_F^2(u,v)$ can be written as [5]

$$\sigma_F^2(u,v) = \sigma^2[\mathrm{ARA}^T]_{u,u}[\mathrm{ARA}^T]_{v,v} \tag{13}$$

where $[\cdot]_{u,u}$ is the (u,u)th component of a matrix, A is given in (2), and R is

$$R = \begin{bmatrix} 1 & \rho & \rho^2 & \rho^3 \\ \rho & 1 & \rho & \rho^2 \\ \rho^2 & \rho & 1 & \rho \\ \rho^3 & \rho^2 & \rho & 1 \end{bmatrix} \tag{14}$$

where ρ is the correlation coefficient and is set to 0.6 in [3]. The DCT coefficients $F(u,v)$ can also be approximately distributed as Gaussian and will be quantized to zeros with a probability controlled by γ in the following form:

$$\gamma\sigma_F(u,v) < T(u,v), \quad 0 \le u,v \le 3. \tag{15}$$

If $\gamma = 3$, then the probability of the DCT coefficient equal to zero after Q is about 99.73%, and a criterion with SAD for early detecting ZQDCT coefficient in (u,v) is

$$\mathrm{SAD} < TS^g(u,v) \tag{16}$$

where

$$TS^g(u,v) = \frac{\sqrt{2}N}{\gamma\sqrt{\pi[\mathrm{ARA}^T]_{u,u}[\mathrm{ARA}^T]_{v,v}}} \cdot T(u,v). \tag{17}$$

III. Proposed ZQDCT Early Detection Approach Using SATD

In H.264/AVC, if the Hadamard transform is enabled for mode decision, after the inter- or intra-prediction only the SATD is available as the distortion measure calculated as

$$\mathrm{SATD} = \frac{1}{2}\sum_{u=0}^{3}\sum_{v=0}^{3}|B(u,v)|. \tag{18}$$

B is the 4 × 4 Hadamard transformed residue block given as

$$B = HfH^T \tag{19}$$

where H is given in (5) and f is the residue block. In other words, SAD is not available before performing DCT and Q. Therefore, the SAD based early detection approaches such as [1]–[3] can not be applied to reduce redundant DCT and Q computations when the Hadamard transform is enabled for H.264/AVC mode decision. To address this problem, we propose a SATD based ZQDCT early detection approach as follows.

A. ZQDCT Prediction for Normal4 $\times$ 4 Type

First, we extend and apply the Gaussian distribution based approach [3] so as to derive efficient conditions by using SATD to predict ZQDCT coefficients for the Normal4 $\times$ 4 type.

For the sake of simplicity and mathematical maneuverability, the Hadamard transformed residual signal x_B [see (19)] is also assumed as Gaussian distributed with zero mean and variance σ_B^2. Therefore, similar to (11) the expected value of $|x_B|$ can be calculated as

$$E[|x_B|] = \sqrt{\frac{2}{\pi}}\sigma_B. \tag{20}$$

Since 2SATD $= \sum_{u=0}^{3}\sum_{v=0}^{3}|x_B(u,v)|$, $E[|x_B|]$ can be approximated as

$$E[|x_B|] \approx \frac{2\text{SATD}}{N} \tag{21}$$

where N is the number of coefficients. Hence, from (20) and (21) we can get

$$\sigma_B \approx \frac{\sqrt{2\pi}\text{SATD}}{N}. \tag{22}$$

According to [5], we have

$$\begin{aligned}\sigma_B^2(u,v) &= Q(u,v)\sigma^2\\ Q(u,v) &= [HRH^T]_{u,u}[HRH^T]_{v,v}\end{aligned} \tag{23}$$

where σ^2 is the variance of the residue signal; H and R are defined in (5) and (14), respectively. From (23), we have

$$\begin{aligned}E[\sigma_B] &\approx \frac{\sum_{i=0}^{3}\sum_{j=0}^{3}\sigma_B(i,j)}{N}\\ &\approx \frac{\sigma}{N}\cdot\left(\sum_{i=0}^{3}\sum_{j=0}^{3}\sqrt{Q(i,j)}\right).\end{aligned} \tag{24}$$

Considering (22) and (24), since $\sigma_B = E[\sigma_B]$, we have

$$\sigma \approx \frac{\sqrt{2\pi}}{\sum_{i=0}^{3}\sum_{j=0}^{3}\sqrt{Q(i,j)}}\cdot\text{SATD}. \tag{25}$$

Recall that the variance of the (u,v)th DCT coefficient $\sigma_F^2(u,v)$ is given in (13). After inserting σ given in (25) into (13), we obtain

$$\sigma_F(u,v) \approx \frac{\sqrt{2\pi\cdot[\text{ARA}^T]_{u,u}[\text{ARA}^T]_{v,v}}}{\sum_{i=0}^{3}\sum_{j=0}^{3}\sqrt{Q(i,j)}}\cdot\text{SATD}. \tag{26}$$

Therefore, after considering (26) and (15), a criterion for ZQDCT coefficient prediction in (u,v) is

$$\text{SATD} < T_s(u,v) \tag{27}$$

where

$$T_s(u,v) = \frac{\sum_{i=0}^{3}\sum_{j=0}^{3}\sqrt{Q(i,j)}}{\gamma\sqrt{2\pi\cdot[\text{ARA}^T]_{u,u}[\text{ARA}^T]_{v,v}}}\cdot T(u,v). \tag{28}$$

As given in (9), it can be proved that $T(u,v) = T(v,u)$ because the multiplication factor matrix M is symmetric. Therefore, we can easily prove that the threshold matrix T_s in (28) is a symmetric matrix (i.e., $T_s(u,v) = T_s(v,u)$), and the following formula holds true:

$$m > n \Rightarrow T_s(u,m) > T_s(u,n). \tag{29}$$

Comparing the SAD-based threshold $TS^g(u,v)$ in (17) and the SATD based threshold $T_s(u,v)$ in (28), we obtain

$$\begin{aligned}\frac{T_s(u,v)}{TS^g(u,v)} &= \frac{\sum_{i=0}^{3}\sum_{j=0}^{3}\sqrt{Q(i,j)}}{2N}\\ &= \frac{55.16}{2\times 16}\\ &= 1.72.\end{aligned} \tag{30}$$

From (30), it is observed that the SATD based threshold $T_s(u,v)$ is larger than the corresponding SAD based threshold $TS^g(u,v)$ and the ratio of $T_s(u,v)$ to $TS^g(u,v)$ is fixed (i.e., 1.72) regardless of the position (u,v).

B. Zero DC Prediction for LumaDC4 $\times$ 4 and ChromaDC2 $\times$ 2 Types

All the DC coefficients of the LumaDC4 $\times$ 4 and ChromaDC2 $\times$ 2 types undergo another Hadamard transform and are quantized differently compared with the Normal4 $\times$ 4 type. Thus, we need to study the sufficient conditions to detect zero quantized DC coefficients for these two types.

The LumaDC4 $\times$ 4 type is studied first. From (6), the quantized DC coefficient $Z_4(u,v)$ is zero if

$$|Y_4(u,v)| < 2\cdot\frac{2^{\text{qbits}} - c}{M(0,0)} = 2T(0,0). \tag{31}$$

After analyzing (4), we can obtain

$$|Y_4(u,v)| \le \frac{1}{2}\sum_{i=0}^{3}\sum_{j=0}^{3}|F_4(i,j)|, \quad 0 \le u,\, v \le 3 \tag{32}$$

where $F_4(i,j)$ is the DC coefficient of the (i,j)th 4×4 block in a 16×16 MB. According to (19), we obtain

$$F_4(i,j) = B_{i,j}(0,0) \tag{33}$$

TABLE I
IMPLEMENTATION OF DCT, Q, IQ, AND IDCT FOR H.264/AVC NORMAL4 × 4 TYPE

Type	Condition	DCT, Q, IQ and IDCT
Skip	$SATD < T_s(0,0)$	Not performed.
1×1	$T_s(0,0) \leq SATD < T_s(0,1)$	Only calculate the DC coefficient.
2×2	$T_s(0,1) \leq SATD < T_s(0,2)$	Only calculate 2×2 low frequency coefficients.
3×3	$T_s(0,2) \leq SATD < T_s(0,3)$	Only calculate 3×3 low frequency coefficients.
4×4	$T_s(0,3) \leq SATD$	Calculate all 16 coefficients.

TABLE II
REQUIRED COMPUTATIONS OF DCT/Q/IQ/IDCT AND ADDITIONAL OVERHEADS INTRODUCED BY THE PROPOSED APPROACH

DCT/Q/IQ/IDCT Implementation				
	ADD	MUL	SFT	CMP
4×4	192	32	112	64
3×3	147	18	76	50
2×2	108	8	58	40
1×1	57	2	37	34
Overheads - Normal4×4 Type				
	ADD	MUL	SFT	CMP
Ours	0	0	0	[1,4]
Overheads - LumaDC4×4 or ChromaDC2×2 Type				
	ADD	MUL	SFT	CMP
Ours	0	0	0	[2,3]

where $B_{i,j}$ is the (i,j)th 4×4 Hadamard transformed residue block in a 16×16 MB. Since

$$|B_{i,j}(0,0)| \leq \sum_{u=0}^{3}\sum_{v=0}^{3}|B_{i,j}(u,v)|,$$
$$\sum_{u=0}^{3}\sum_{v=0}^{3}|B_{i,j}(u,v)| = 2\mathrm{SATD}_{i,j} \tag{34}$$

and considering (32) and (33), we obtain

$$|Y_4(u,v)| \leq \frac{1}{2}\sum_{i=0}^{3}\sum_{j=0}^{3} 2\mathrm{SATD}_{i,j} = \mathrm{SATD}_{16} \tag{35}$$

where $\mathrm{SATD}_{i,j}$ is the SATD of the (i,j)th 4×4 block in a 16×16 MB; SATD_{16} is the SATD of a 16×16 MB. Considering (31) and (35), we derive

$$\mathrm{SATD}_{16} < 2T(0,0) \tag{36}$$

under which all the DC coefficients of the LumaDC4 × 4 type are quantized to zeros.

In a similar manner, we can derive the sufficient condition for detecting zero quantized DC coefficients for the ChromaDC2 × 2 type as follows:

$$\mathrm{SATD}_{4c} < T(0,0) \tag{37}$$

where SATD_{4c} is the SATD of an 8×8 chroma block.

C. Implementation of the Proposed Approach

Similar to [3], we can use four thresholds $T_s(0,0)$, $T_s(0,1)$, $T_s(0,2)$ and $T_s(0,3)$ to execute five types of DCT, Q, IQ and IDCT implementations: *Skip*, 1×1, 2×2, 3×3 and 4×4 as described in Table I in order to reduce computations for the Normal4 × 4 type.

As for the LumaDC4 × 4 and ChromaDC2 × 2 types, the implementation schemes should be modified as compared with the implementation scheme for the Normal4 × 4 type. Specifically, the implementation conditions for the *Skip* and 1×1 types should be refined by considering the conditions in (36) and (37). For example, the modified *Skip* implementation condition for the LumaDC4 × 4 type is $\mathrm{SATD} < T_s(0,1)$ && $\mathrm{SATD}_{16} < 2T(0,0)$. The modified 1×1 implementation condition for the LumaDC4 × 4 type is $\mathrm{SATD} < T_s(0,1)$ && $\mathrm{SATD}_{16} \geq 2T(0,0)$.

As mentioned in [3], the implementation of DCT, Q, IQ and IDCT can be optimized according to the implementation types. To illustrate the number of computations for different types of DCT/Q/IQ/IDCT implementations occurred in the reference software JM9.5 [6], the number of addition (ADD), multiplication (MUL), shift (SFT) and comparison (CMP) operations are listed in Table II. It should be noted that additional overheads are introduced by the proposed approach. Since the thresholds $T_s(0,i), 0 \leq i \leq 3, T(0,0)$ and $2T(0,0)$ are pre-computed and used by a look-up table and all the SATD values are available before DCT and Q, the overheads as compared with the original encoder include only the comparison operations for determining different types of DCT/Q/IQ/IDCT implementations. For clear description, the overheads are also listed in Table II.

IV. EXPERIMENTAL RESULTS

In order to evaluate the proposed approach, the reference software JM9.5 [6] is used for experiments. Fast ME is enabled and the number of reference frames is set to 1. All the block search sizes are enabled for mode selection. The R-D optimization is disabled and the CAVLC coding is enabled. For testing the proposed SATD based approach,[1] the Hadamard transform is enabled. Due to the space limit, the results of four benchmark video sequences with CIF format are presented. They are "News," "Foreman," "Bus," and "Mobile Calendar." Each of the test video sequences has 100 frames to be encoded. The GOP structure is IPPP without using B-frames and the period of I-frames is 10. In order to examine the performance at different bit rates, five Q_p values, 24, 28, 32, 36, and 40, are employed in our experiments.

First, the percentage of encoding time consumed by DCT, Q, IQ and IDCT functions is shown in Table III, where the average percentage value under the five Q_p test conditions is given for each of the video sequences. From Table III, the percentage of

[1]In the H.264/AVC reference software JM9.5, the proposed approach can be applied to intra/inter-luma blocks and intra-chroma blocks. When the chroma blocks are encoded with inter-modes, the proposed approach can not be applied since the SATD information is not available for the chroma blocks. This is because only the SATD values of luma blocks are utilized for searching the best encoded inter-modes.

TABLE III
PERCENTAGE OF ENCODING TIME IN DCT, Q, IQ, AND IDCT

News	Foreman	Bus	Mobile Calendar
5.61%	4.49%	4.07%	4.29%

TABLE IV
RESULTS OF PZQ, FRR, AND FAR

	News			Foreman		
Q_p	PZQ	FRR	FAR	PZQ	FRR	FAR
24	95.40%	46.28%	0.26%	94.01%	65.11%	0.18%
28	96.86%	37.65%	0.54%	96.48%	49.63%	0.29%
32	97.93%	31.25%	0.91%	97.97%	36.82%	0.57%
36	98.67%	26.59%	1.97%	98.79%	27.95%	1.31%
40	99.14%	22.73%	4.72%	99.26%	22.20%	2.99%
	Bus			**Mobile Calendar**		
Q_p	PZQ	FRR	FAR	PZQ	FRR	FAR
24	85.48%	83.50%	0.11%	77.74%	78.13%	0.07%
28	90.73%	72.26%	0.28%	84.83%	72.62%	0.11%
32	94.52%	58.98%	0.75%	90.71%	66.00%	0.27%
36	96.86%	46.38%	1.48%	94.72%	57.27%	0.57%
40	98.22%	35.55%	2.69%	97.10%	47.05%	1.18%
On Average:			**FRR = 49.20%**		**FAR = 1.06%**	

DCT, Q, IQ and IDCT encoding time on average for all the four video sequences is about 4.62%.

The false rejection rate (FRR) and false acceptance rate (FAR) are provided to compare the prediction capacity of ZQDCT coefficients for the proposed approach

$$\mathrm{FRR} = \frac{N_{mz}}{N_z} \times 100\%, \quad \mathrm{FAR} = \frac{N_{mn}}{N_n} \times 100\%. \tag{38}$$

N_{mz} is the number of ZQDCT coefficients being miss classified as non-ZQDCT coefficients, N_z is the total number of ZQDCT coefficients, N_{mn} is the number of non-ZQDCT coefficients being miss classified as ZQDCT coefficients, and N_n is the total number of non-ZQDCT coefficients. It is desirable to have small FRR and FAR values for efficient prediction approaches.

The FRR and FAR results are given in Table IV. In addition, the percentage for ZQDCT coefficients (PZQ), i.e., $\mathrm{PZQ} = N_z/(N_z + N_n) \times 100\%$, is also listed in Table IV. From the results, the following conclusions can be drawn. Firstly, the ZQDCT coefficients occupy a great portion of the whole. And along with the increase of Q_p, more DCT coefficients are quantized to zeros. Secondly, with the increase of Q_p, the proposed approach is able to predict ZQDCT coefficients more efficiently. This can be observed by studying the FRR results for each of the test video sequences. Thirdly, as for the FAR results, with the increase of Q_p, the FAR becomes a little bit worse. However, since the value of N_n is relatively very small as compared with N_z, the improvement of prediction efficiency in terms of FRR becomes more significant. Moreover, the FAR results of the proposed approach are so insignificant that almost no video quality degradation is observed by the proposed approach (we will present the video quality performance as follows). On average, the FRR and FAR obtained by the proposed approach are 49.20% and 1.06%, respectively.

Next, we study the encoded video quality and bit rates resulted from the proposed approach. The video quality is objectively evaluated in terms of the peak signal-to-noise ratio (PSNR, dB). The performances of PSNR and bit rates are presented in the following form:

$$\Delta P = P - P_{\mathrm{org}}, \quad \Delta R = \frac{R - R_{\mathrm{org}}}{R_{\mathrm{org}}} \times 100\% \tag{39}$$

where P and P_{org} are the PSNR criterion of the proposed approach and the original encoder, respectively; R and R_{org} are the encoded bit rates of the proposed approach and the original encoder, respectively. The PSNR and bit rates results are given in Table V. From the results, the average PSNR loss is 0.025 dB with the maximum PSNR loss of 0.124 dB and thus negligible. Moreover, the average bit rate has been reduced by 0.22% on average, which indicates that the proposed approach can achieve better bit rate performance than the original encoder. The R-D curves of the original encoder and the proposed approach are also compared according to the calculation method [7]. The comparison results demonstrate that the proposed approach achieves almost the same R-D performance as the original encoder.

TABLE V
PSNR DEGRADATION ΔP (dB) AND BIT RATES REDUCTION ΔR (%)

	News		Foreman		Bus		Mobile Calendar	
Q_p	ΔP	ΔR	ΔP	ΔR	ΔP	ΔR	ΔP	ΔR
24	-0.021	0.04	-0.002	-0.18	-0.005	-0.08	-0.003	-0.05
28	-0.037	-0.02	-0.004	-0.23	-0.016	-0.23	-0.004	0
32	-0.030	-0.12	-0.006	-0.22	-0.018	-0.25	-0.012	-0.19
36	-0.124	-0.36	-0.004	-0.05	-0.029	-0.42	-0.014	-0.20
40	-0.098	-0.83	-0.026	-0.04	-0.040	-0.74	-0.012	-0.16
On Average:			**ΔP = -0.025**				**ΔR = -0.22**	

TABLE VI
AVERAGE RESULTS OF C_r AND ΔT

Sequence	ADD	MUL	SFT	CMP	ΔT
News	44.77%	35.97%	47.18%	50.93%	3.04%
Foreman	54.19%	43.05%	56.60%	61.33%	2.04%
Bus	72.91%	63.03%	74.61%	80.47%	1.05%
Mobile Calendar	75.31%	69.94%	76.45%	81.91%	1.00%
On Average	**61.80%**	**53.00%**	**63.71%**	**68.66%**	**1.78%**

Finally, the computational complexity of DCT, Q, IQ and IDCT procedures C_r and the overall encoding time improvement ΔT are studied via the following criteria:

$$C_r = \frac{O_t}{O_o} \times 100\%, \quad \Delta T = \frac{T_o - T_t}{T_o} \times 100\% \tag{40}$$

where O_t is the number of one of the following operations: ADD, MUL, SFT, and CMP, required in DCT, Q, IQ, and IDCT of the proposed approach; O_o is the number of the corresponding operations of the original encoder; T_o is the overall encoding time of the original encoder; T_t is the overall encoding time when the proposed approach is applied. Note that the overheads for implementing the proposed approach, i.e., the CMP operations listed in Table II have been already considered into the counting of number of operations for the proposed approach. The average results of C_r and ΔT for each of the test sequences are given in Table VI, where we can see that the proposed approach can reduce the computations of DCT, Q, IQ, and IDCT by 30%–40% on average and can reduce the overall encoding time by 1.78% on average.

V. Conclusion

In this paper, an efficient approach is presented to predict ZQDCT coefficients in order to reduce redundant computations for H.264/AVC encoding. Unlike all the other ZQDCT prediction approaches which employ the SAD information, the proposed approach utilizes the SATD information for prediction. When the Hadamard transform is enabled for H.264/AVC mode decision, only the SATD instead of SAD is available prior to DCT and Q, and hence only the proposed approach can be applied to reduce DCT and Q computations as compared with other ZQDCT prediction approaches in the literature. The experimental results have demonstrated that the proposed approach can greatly reduce the DCT, Q, IQ, and IDCT computations and achieves almost the same R-D performance as the original encoder.

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