A Novel DCT architecture for Quality and Power Efficient

B. Y. Lin*, C. C. Sung*, S. J. Ruan*† and M. C. Shie*
*Department of Electronic Engineering
National Taiwan University of Science and Technology, Taipei 106, Taiwan
†Tel: +886-2-27376411, E-mail:sjruan@et.ntust.edu.tw

***Abstract*— In recent years, the demand for multimedia mobile battery-operated devices has created a need for low power implementation of video compression. Many video compression standards require the discrete cosine transform (DCT) function to perform image/video compression. For this reason, low power DCT design has become more and more important in today's image/video processing. This paper presents a new power-efficient Hybrid DCT architecture which combines Loeffler DCT and binDCT in terms of special property on luminance and chrominance difference.**

We use Synopsys PrimePower to estimate the power consumption in a TSMC 0.25-μm technology. Besides, we also adopt a novel assessment method based on structural distortion measurement to measure the video quality instead of peak signal to noise rations (PSNR) and mean squared error (MSE). It is concluded that our Hybrid DCT offers similar video quality performance to the Loeffler, and leads to 18% power consumption and 27% chip area savings.

I. INTRODUCTION

In recent years, many kinds of digital image processing and video compression techniques have been proposed in the literature[1]. New generation video and audio compression standards are proposed to replace early compression methods, such as MP3, MPEG 4 and H.264 for higher quality and better performance. All the above standards require the discrete cosine transform (DCT) function [2] to perform image/video compression which translates from space domain to frequency domain. Also, modern mobile device executing multimedia applications consumes a significant amount of power. For this reason, low power DCT design has become more and more important in today's image/video processing.

On the past few years, many researches have devoted to the low power DCT design [3], [4], [5], [6], [7], [8], [9], [10]. Distributed arithmetic architecture (DAA) and flow-graph algorithm (FGA) are the most popular approaches for implementing fast DCT (FDCT) [11], [12], [13], [14], [15], [16]. While the area advantages of DAA are well known, which should be best suited for power-dominated applications. On the contrary, the DAA actually consumes more power than FGA[17]. Therefore, the FGA has better power efficient and is more suitable for low power consideration[18]. Loeffler proposed a low-complexity FDCT/IDCT algorithm based on FGA that required only 11 multiplications and 29 additions [15]. However, the power consumption of multiplication accounts for about 40% in DCT computation, and almost occupies 45% of total area. Due to the observation of multiplication operation dissipated a large amount of power, Tran proposed binDCT which replaced multiplication with shifter[19]. It consumed about 38% less power than that of Loeffler DCT.

On the basis of quality analysis, peak signal to noise rations (PSNR) and mean squared error (MSE) are simple and well-known for estimating image quality. However, large errors do not always result in poor perceptual distortions and visual sensitive [20], [21], [22]. So we adopt a novel assessment method based on structural distortion measurement to measure the quality of compressed results [23]. Notice that novel assessment method is more consistent with human visual system behavior compared with PSNR.

As we know that human visual behavior is less sensitive to chrominance resolution than luminance resolution. In this paper, we propose a Hybrid DCT processing architecture which combines the Loeffler DCT and the binDCT in terms of special property on luminance and chrominance difference. In order to reduce power consumption, we employ the binDCT to handle the chrominance stream. On the other hand, we employ the Loeffler DCT to handle the luminance stream for the reason to keep video quality. The power-efficient hybrid design reduces not only power consumption but also chip area compared with the Loeffler DCT. Moreover, our Hybrid DCT can get better video quality than binDCT. The power efficient and high video quality characteristics of the Hybrid DCT are especially suitable for hi-end design, such as mobile handsets, DVD recorder, digital camera and wireless set-top box.

The rest of this paper is organized as follows. Section 2 briefly introduces the algorithms of Loeffler DCT and binDCT. In section 3, we present the detailed Hybrid DCT architecture and its functional block. Section 4 presents the power analysis and video quality measurements while section 5 concludes this paper.

II. DCT ALGORITHMS

A. The DCT Backgroud

The two dimensional DCT in equation 1 transforms an 8×8 block of video frame samples from spatial domain $f(x,y)$ into frequency domain $F(k,l)$.

$$F(k,l) = \frac{1}{4}C(k)C(l)\sum_{x=0}^{7}\sum_{y=0}^{7} f(x,y) \cos[\frac{(2x+1)k\pi}{16}]\cos[\frac{(2y+1)l\pi}{16}] \tag{1}$$

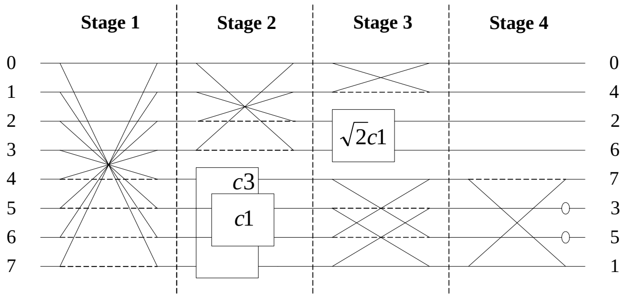

Fig. 1. Loeffler's FDCT algorithm[15].

$$C(k) = \begin{cases} \frac{1}{\sqrt{2}} & \text{, if } k = 0 \\ 1 & \text{, otherwise.} \end{cases}$$
$$C(l) = \begin{cases} \frac{1}{\sqrt{2}} & \text{, if } l = 0 \\ 1 & \text{, otherwise.} \end{cases}$$

Since computing the above 2-D DCT by using matrix multiplication requires 8^4 multiplications, a commonly used approach in hardware designs to reduce the computation complexity is row-column decomposition. The decomposition performs row-wise one-dimensional (1-D) transform followed by column-wise 1-D transform with intermediate transposition. An 8-point 1-D DCT can be expressed as follow:

$$F(k) = \frac{1}{2}C(k)\sum_{x=0}^{7} f(x)\cos[\frac{(2x+1)k\pi}{16}]$$
$$C(k) = \begin{cases} \frac{1}{\sqrt{2}} & \text{, if k = 0} \\ 1 & \text{, otherwise.} \end{cases} \tag{2}$$

This decomposition approach has two advantages. First, the number of operations is reduced. Second, the 1-D DCT can be readily manipulated to further streamline the number of operations.

B. Loeffler DCT Algorithm

Many 1-D flow graph algorithms have been reported in the literature. These papers aimed at reducing the number of multiplications because general-purpose multiplier is assumed to be the major power consumption for the computation in the DCT. Therefore, choosing a suitable algorithm that minimizing the number of multiplications to achieve low-power is very important. Table I summarizes the complexity of several flow-graph algorithms[24]. Since the number of multipliers in Loeffler's algorithm reaches the theoretical lower bound, we select the Loeffler DCT algorithm to handle the luminance stream in our Hybrid DCT.

As we can see in Table I, Loeffler's 1-D eight-point DCT algorithm uses only 11 multiplications and 29 additions. Figure 2 describes the transfer functions of the building blocks. The second building block (kcn), the rotation, can be calculated with only 3 multiplications and 3 additions instead of 4 multiplications and 2 additions by using equation 3.

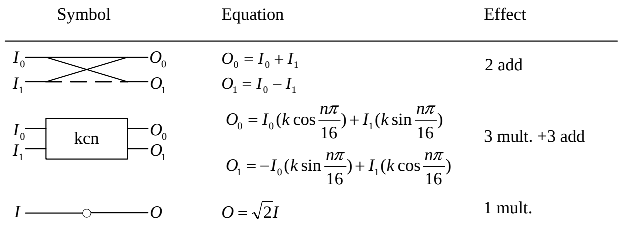

Fig. 2. Transfer function of Loeffler's FDCT building blocks[15].

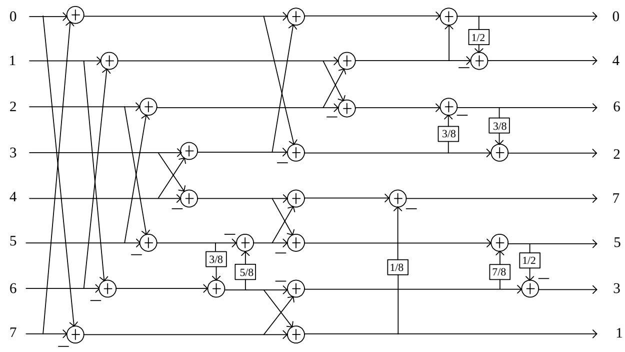

Fig. 3. binDCT-c algorithm[30].

$$\begin{aligned} O_0 &= aI_0 + bI_1 = (b-a)I_1 + a(I_0+I_1) \\ O_1 &= -bI_0 + aI_1 = -(a+b)I_0 + a(I_0+I_1) \\ &\begin{cases} a = k\cos[\frac{n\pi}{16}] \\ b = k\sin[\frac{n\pi}{16}] \end{cases} \end{aligned} \tag{3}$$

C. The binDCT Algorithm

Although DCT is very useful for image/video compression, it can not map integers to integers without losses due to that DCT is a floating-point transform. More importantly, hardware implementations of floating-point algorithms need more area and power consumption. Therefore, integer-friendly approximations of the DCT are necessary[19], [29].

Tran presented a fast biorthogonal block transform called binDCT that can be implemented by using only shift and add operations (i.e. there is no multiplication). The binDCT is an approximation of the DCT and can map integers to integers with exact reconstruction. This property is pivotal in transform-based lossless coding and allows a unifying lossless coding framework.

Table II compares three different versions of the binDCT[30]. Among the three versions of binDCT, we can observe that the binDCT-c has the lowest number of operations. Therefore, we select this version to handle the chrominance stream in our Hybrid DCT. Figure 3 shows the flow graph of binDCT-c architecture.

TABLE I
Complexities of different FDCT algorithms[24].

Algorithm	Chen[14]	Wang[16]	Lee[13]	Vetterli[25]	Suehiro[26]	Hu[27]	Loeffler[15]	Jeong[28]
Multiplier	16	13	12	12	12	12	11	12
Adder	26	29	29	29	29	29	29	28

TABLE II
Comparion Of binDCT Transform Complexity.

Transform	No. of Adders	No. of Shifters
8 x 8 binDCT-a	36	19
8 x 8 binDCT-b	31	14
8 x 8 binDCT-c	30	13

TABLE III
Compartion between the Loeffler DCT and the binDCT.

	Area	Power	Distortion Rate
Loeffler DCT	poor	poor	good
binDCT	good	good	poor

Table III compares the area, power consumption, and distortion rate of Loeffler DCT and binDCT architectures.

D. Loeffler DCT vs. binDCT

In Table III, we compare the area, power consumption, and distortion rate between Loeffler DCT and binDCT. The Loeffler DCT implements the DCT architecture by using multipliers and adders. Although multiplier will introuduce more power dissipation and area, it can offer better distortion rate. On the other hand, the binDCT employs the shifter and adder to approach the multiply operation by using appropriate dyadic lifting steps [31]. Hence the binDCT will result in more image distortion than the Loeffler DCT[30]. Even then the binDCT has less power consumption and area than that of the Loeffler DCT.

In next section, we will take advantage of Loeffler DCT and binDCT algorithms and separate the luminance stream and chrominance stream to build our Hybrid DCT architecture.

III. Hybrid DCT Architectures

As shown in Table III, the power consumption and the distortion rate between Loeffler DCT and binDCT have its merits. Notice that the different properties of distortion rate will reflect on video quality. Moreover, as we mentioned in section I, the human visual system is less sensitive to chrominance resolution than luminance resolution. In accordance with the different special properties of these algorithms, we propose a hybrid method that combines the Loeffler DCT and the binDCT based on special properties on luminance and chrominance difference.

Our Hybrid DCT architecture is shown in Figure 4, we separate the video to luminance (Y) and chrominance (CbCr) streams for high quality and low-power. Notice that luminance and chrominance streams in traditional design are already separated. In order to get better video quality, we employ the Loeffler DCT which has less distortion rate to handle the luminance stream. On the other hand, for the reason to reduce power consumption, we employ the binDCT which has large distortion rate to handle the chrominance stream. Although binDCT will decrease video color quality, the influences of color defect are almost unnoticed on video sequence stream or digital image compression. All of these amount to saying that we use the Loeffler DCT to keep the image quality and use the binDCT to reduce power consumption and chip area.

We desire the power dissipation of Hybrid DCT performs between Loeffler DCT and binDCT. However, we also hope that the video quality of Hybrid DCT can get close to Loeffler DCT. So we combine two different algorithms to design our Hybrid DCT for low-power, high throughput, and reasonable video quality.

Finally, we exchange the luminance and the chrominance input streams without changing the Hybrid DCT architecture named inv-Hybrid DCT to prove our hybrid method is reasonable good as shown in Figure 5.

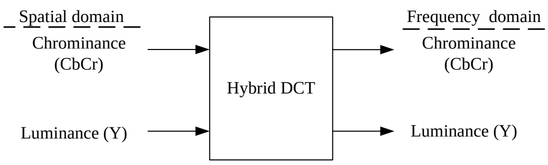

Fig. 5. inv-Hybrid DCT architecture.

IV. Results

A. Experiment Environment

In order to analyze the performance of our hybrid architecture, we modeled four architectures: Loeffler DCT, binDCT, Hybrid DCT, and inv-Hybrid DCT. We built the RTL codes and functions of the architectures. After synthesizing with TSMC 0.25-μm technology library, we used Synopsys PrimePower to estimate power consumption. In addition, we also simulated the gate level circuits with H.263 qcif video pattern

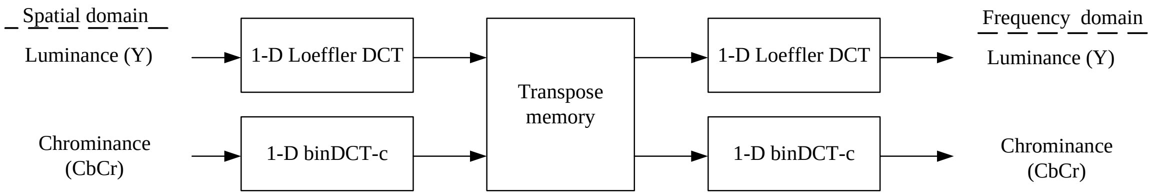

Fig. 4. Hybrid DCT architecture.

TABLE IV
POWER AND AREA RESULTS.

	Loeffler DCT	Hybrid DCT	binDCT
Power(mW)	90.29	74.04	56.20
Area(GateCount)	125K	91K	58K

TSMC 0.25-μm at 2.5V and 33.3Mhz with 8-stage pipeline.

and dumped the value change dump to do the power analysis for accurate.

B. Video Quality

Next we evaluate the average of PSNR by means of sampling rate of luminance and chromance. The PSNR is widely used because it is simple to calculate, has clear physical meanings, and is mathematically easy to deal with for optimization purposes. However, it has been widely criticized as well for not correlating well with perceived quality measurement[20], [21], [22]. Therefore, we adopt a novel video quality assessment method based on structural distortion measurement to verify our designs[23]. From an image formation point of view, the “structural distortion” in an image as those attributes that reflect the structure of the object in the scene, which is independent of the average luminance and contrast of the image. This leads to an image quality assessment approach that separates the measurement of luminance, contrast and structural distortions. The approach is called Structural SIMilarity (SSIM) index. Then the SSIM indexing approach is applied to Y, Cb and Cr color components independently and combined into a local quality measure using a weighted summation.

The diagram of the video quality assessment is shown in Figure 6. The quality of the distorted video is measured in three levels: the local region level, the frame level, and the sequence level. More importantly, the novel assessment method considers not only the measurement of luminance, contrast, and structural distortions, but also another two weight adjustments. The first is based on the observation that dark regions usually do not attract fixations, and therefore should be assigned smaller weight. The second adjustment considers the case when very large global motion occurs. And we should assign smaller weights to large motion frames in order to improve robustness of architecture.

The overall quality of the video sequence is given in equation 4.

$$Q = \frac{\sum_{i=1}^{F} W_i Q_i}{\sum_{i=1}^{F} W_i} \tag{4}$$

where F is the number of frames, W_i is the weighing value assigned to the i-th frame and the Q_i denotes the quality index measure of the i-th frame in the video sequence. The equation satisfies following conditions:

1) $Q \leq 1$;
2) $Q = 1$, if and only if video has no distortion.

However, we assume all the local weights and all the frame weights are equal in our experiments. Even then, the algorithm does not have significant effect on the overall performance. All in all, the novel assessment method has been found to be consistent with many observations of human visual system behaviors.

C. Experiment Results

In our experiments, we used the H.263 video patterns to evaluate these four architectures. Table IV compares the area and the power consumption of these architectures. Since Hybrid DCT keeps the precise of luminance by Loeffler DCT, the area and the power consumption are inferior to binDCT. Table V shows the average PSNR and the novel video quality measurement results. Although the Loeffler DCT architecture can obtain the optimal video quality, it consumes more around 37% area and 21% power dissipation than Hybrid DCT architecture.

Figure 7 shows the average video qualities and the power consumptions of these four DCT architectures. It can be easily noticed from Figure 7 that the Hybrid DCT architecture performs middle power consumption between Loeffler DCT and binDCT, however the video quality is close to Loeffler DCT. It implies that Hybrid DCT has better tradeoff between Loeffler DCT and binDCT. On the contrary, the video quality and the power dissipation of inv-Hybrid DCT are worse than Hybrid DCT as we expected. In sum, the Hybrid DCT correctly separates the luminance stream (Y) and the chrominance stream (CbCr) not only obtains well video quality but reduces power dissipation and chip area.

V. CONCLUSION

In this paper, we proposed a power-efficient Hybrid DCT architecture which separates the luminance and the chrominance channels. We integrated Loeffler DCT and binDCT algorithms

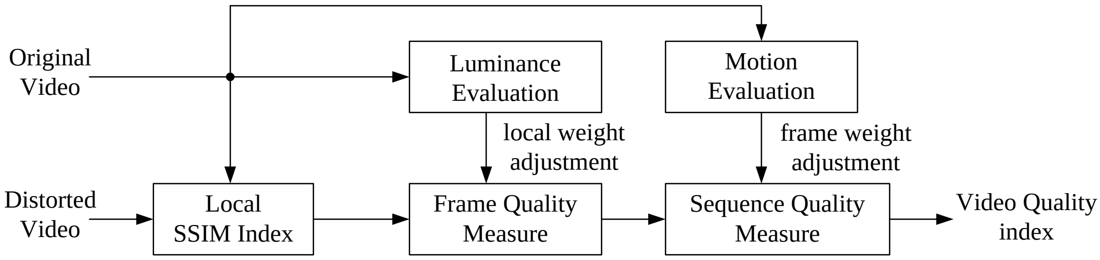

Fig. 6. The video quality assessment system[23].

TABLE V
VIDEO QUALITY ANALYZE RESULTS.

	Loeffer DCT		**Hybrid DCT**		**inv-Hybrid DCT**		**Bin DCT**	
	PSNR	Q	PSNR	Q	PSNR	Q	PSNR	Q
News	46.4	0.9926	44.72	0.9887	44.61	0.9832	42.95	0.9792
Foreman	46.2	0.9936	44.58	0.9898	44.46	0.9872	42.85	0.9834
Container	46.7	0.9912	45	0.9870	44.80	0.9808	43.1	09766

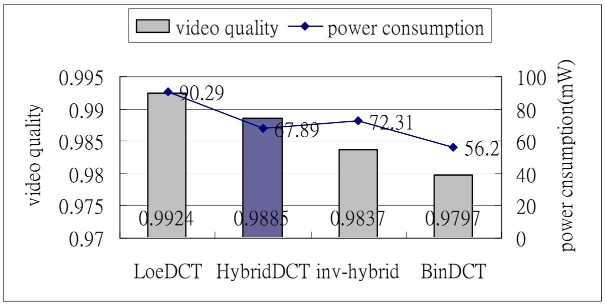

Fig. 7. The average performance comparisons of these architectures.

to reduce power consumption and chip area, however keep reasonable video quality. We adopt a novel assessment method to evaluate video quality instead of PSNR and MSE. Finally, our experimental results clearly indicate that the Hybrid DCT offers similar performance to the Loeffler DCT in terms of the video quality. Moreover, the Hybrid DCT leads to 18% power and 27% area savings in comparison with the Loeffler DCT. All in all, the Hybrid DCT provides another choice that can save power consumption, reduce chip area, and keeps the visual quality. It is important to note that our design method can be used in low power and high resolution applications, especially in battery-based systems.

REFERENCES

[1] I. E. G. Richardson, *Video Codec Design*. Atrium, England: John Wiley & Sons Ltd, 2002.
[2] R. Conzalez and R. Woods, *Digial Image Processing*. New Jersey: Prentice-Hall, Inc., 2001.
[3] L. J. and S. L. Lu, "Low power design of two-dimensional dct," in *IEEE Conf. on ASIC and Exhibit*, Sept. 1996, pp. 309–312.
[4] A. N.J. and D. S. Ha, "Low power design of dct and idct for low bit rate video codecs," *IEEE Transactions on Multimedia*, vol. 6, pp. 414–422, June 2004.
[5] J. Park, S. Kwon, and R. K., "Low power reconfigurable dct design based on sharing multiplication," in *IEEE International Conf. on Acoustics, Speech, and Signal Processing*, vol. 3, May 2002, pp. III–3116 – III–3119.
[6] X. T. and C. A.P., "A low-power dct core using adaptive bitwidth and arithmetic activity exploiting signal correlations and quantization," *IEEE Journal of Solid-State Circuits*, vol. 35, pp. 740–750, May 2000.
[7] K. Kim and B. P.A., "A high-performance low-power asynchronous matrix-vector multiplier for discrete cosine transform," in *IEEE Asia Pacific Conf. on ASICs*, Aug. 1999, pp. 135–138.
[8] H. Jeong, J. Kim, and W. kyung Cho, "Low-power multiplierless dct architecture using image correlation," *IEEE Trans. Consumer Electron.*, vol. 50, pp. 262–267, Feb. 2004.
[9] S. A., P. W., C. A., and B. M.A., "A low power high performance distributed dct architecture," in *IEEE Computer Society Annual Symposium on VLSI*, Apr. 2002, pp. 21–27.
[10] F. L. and S. S., "Data driven vlsi computation for low power dct-based video coding," in *International Conf. on Electronics, Circuits and Systems*, Sept. 2002, pp. 541–544.
[11] S.A., "Applications of distributed arithmetic to digital signal processing: a tutorial review white," *IEEE ASSP Mag.*, vol. 6, pp. 4–19, July 1989.
[12] D. W. Kim, T. W. Kwon, J. M. Seo, J. K. Yu, S. K. Lee, J. H. Suk, and J. R. Choi, "A compatible dct/idct architecture using hardwired distributed arithmetic," in *IEEE International Symposium on Circuits and Systems*, vol. 2, May 2001, pp. 457–460.
[13] B. Lee, "A new algorithm to compute the discrete cosine transform," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 32, pp. 1243–1245, Dec. 1984.
[14] W.-H. Chen, S. C., and F. S., "A fast computational algorithm for the discrete cosine transform," *IEEE Trans. Commun.*, vol. 25, pp. 1004–1009, Sept. 1977.
[15] L. C., L. A., and M. G.S., "Practical fast 1-d dct algorithms with 11-multiplications," in *Proc. ICASSP*, vol. 2, Glasgow,UK, May 1989, pp. 988–991.
[16] Z. Wang, "Fast algorithms for the discrete w transform and for the discrete fourier transform," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 32, pp. 803–816, Aug. 1984.
[17] M. Kuhlmann and K. Parhi, "Power comparison of flow-graph and

distributed arithmetic based dct architectures," in *Signals, Systems & Computers*, vol. 2, CA USA, Nov. 1998, pp. 1214–1219.

[18] E. Farag and M. Elmasry, "Low-power implementation of discrete cosine transform," in *Proceedings of the VLSI*, Canada, Mar. 1996, pp. 174–177.

[19] T. T.D., "A fast multiplierless block transform for image and video compression," in *International Conf. on Image Processing*, Oct. 1999, pp. 822–826.

[20] Z. Wang, A. Bovik, and L. Lu, "Why is image quality assessment so difficult," in *IEEE Conf. on Acoustics, Speech, and Signal Processing*, vol. 4, May 2002, pp. IV–3313 – IV–3316.

[21] Z. Wang and B. A.C., "A universal image quality index," *IEEE Signal Processing Lett.*, vol. 9, pp. 81–84, Mar. 2002.

[22] Z. Wang, L. Lu, and B. A.C., "Video quality assessment using structural distortion measurement," in *IEEE Conf. on Image Processing*, vol. 3, June 2002, pp. III–65 – III–68.

[23] Z. Wang, L. Lu, and A. C. Bovik, "Video quality assessment based on structural distortion measurement," *SIGNAL PROCESSING: IMAGE COMMUNICATION*, vol. 19, pp. 121–132, Feb. 2004.

[24] P. C.-Y., L. W.E., and A.-K. A.J., "Low-power data-dependent 8/spl times/8 dct/idct for video compression," *IEE Proc. Vision, Image and Signal Processing*, vol. 150, pp. 245–255, Aug. 2003.

[25] V. M. and N. H., "Simple fft and dct algorithms with reduced number of operations," *Signal Process*, vol. 6, pp. 264–278, 1984.

[26] S. N. and H. M., "Fast algorithms for the dft and other sinusoidal transforms," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 34, pp. 642–644, 1986.

[27] H. Hou, "A fast recursive algorithm for computing the discrete cosine transform," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 35, pp. 1455–1461, 1987.

[28] Y. Jeong, I. Lee, H. S. Kim, and K. T. Park, "Fast dct algorithm with fewer multiplication stages," *Electronics Letters*, vol. 34, pp. 723–724, 1998.

[29] G. A. Hoffmann, E. E. Fabris, D. Zandonai, and S. Bampi, "The bindct processor," Microelectronics Group.

[30] T. T.D., "The bindct: fast multiplierless approximation of the dct," *IEEE Signal Processing Lett.*, vol. 7, pp. 141–144, June 2000.

[31] J. Liang and T. T.D., "Fast multiplierless approximations of the dct with the lifting scheme," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 49, pp. 3032–3044, Dec. 2001.